International Conference on the Conservation of Grotto Sites

Mogao Grottes at Dunhuang

October 1993Mogao Grottes at Dunhuang

October 1993

PROCEEDINGS

Conservation of Ancient Sites on the Silk Road

The Getty Conservation Institute

Conservation of Ancient Sites on the Silk Road

Proceedings of an International Conference on the Conservation of Grotto Sites

Conference organized by the Getty Conservation Institute, the Dunhuang Academy, and the Chinese National Institute of Cultural Property

Mogao Grottoes, Dunhuang
The People's Republic of China
3–8 October 1993

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THE GETTY CONSERVATION INSTITUTE
LOS ANGELES

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Contents

Miguel Angel Corzo	vii	Foreword
Neville Agnew	ix	Preface
	xiii	Site Map of the Mogao Grottoes at Dunhuang
	xiv	Map of the Silk Road
	xvi	China Dynasty Table
Duan Wenjie	1	Dunhuang Art: The Treasure of the Silk Road
Huang Kezhong	4	An Overview of Protection of Grottoes in China
Fan Jinshi	12	Fifty Years of Protection of the Dunhuang Grottoes
Neville Agnew *Huang Kezhong*	23	Projects of the Getty Conservation Institute and the State Bureau of Cultural Relics *The Mogao and Yungang Grottoes*
Sharon Sullivan	28	KEYNOTE ADDRESS The Management of Ancient Chinese Cave Temples *A Site-Management Training Course at the Yungang Grottoes*
Robertson E. Collins	41	Management of Tourism at Buddhist Sites
Senake Bandaranayake	46	The Dambulla Rock Temple Complex, Sri Lanka *Ten Years of Management, Research, and Conservation*
Jeffrey W. Cody	56	Site-Management Lessons from Canyon de Chelly, Lascaux, Sigiriya, and Bamian
Stephen Rickerby	62	The Role of Documentation in Defining Conservation Strategies at Grotto Sites

Benita Johnson 67 Conservation Survey of the Tam Ting Caves

Sharon Cather 82 KEYNOTE ADDRESS
Complexity and Communication:
Principles of In Situ Conservation

Cynthia Luk
Ingrid Neuman
James Martin
Cynthia Kuniej Berry
Judy Greenfield 95 The Treatment of Two Chinese Wall Painting Fragments

Lore Erwine Fleming 105 Paintings on Silk and Paper from Dunhuang at the British Museum
Conservation Methods

Eric Gordon 112 Conservation Treatment of Two Ming Dynasty Temple Wall Paintings

Gao Nianzu
Jia Ruiguang
Wang Jinyu 120 Research on Protection of Ancient Floor Tiles in the Mogao Grottoes

Sally Malenka
Beth A. Price 127 A Chinese Wall Painting and a Palace Hall Ceiling
Materials, Technique, and Conservation

Constance S. Silver 139 The Conservation of Tempera Mural Paintings and Architectural Finishes

Robert E. Englekirk 147 KEYNOTE ADDRESS
Geotechnical Issues in the Conservation of Sites

Sun Rujian 159 Review of Stabilization Projects at the Mogao Grottoes

Jiang Huaying
Huang Kezhong 170 Stabilization and Consolidation of the Kizil Grottoes

Zhong Shihang 181 Application of Cartridge-Type Grouting in Grotto Conservation

Yi Wuzhi
Lang Xiangui 187 Techniques for Reinforcement of the Maijishan Grottoes

Li Zuixiong
Neville Agnew
Po-Ming Lin 194 Chemical Consolidation of Conglomerate and Sand at the Mogao Grottoes

Ling Yuquan *Qu Jianjun* *Fan Jinshi* *Li Yunhe*	213	Research into the Control of Damage by Windblown Sand at the Mogao Grottoes
Po-Ming Lin *Neville Agnew* *Li Yunhe* *Wang Wanfu*	227	Desert-Adapted Plants for Control of Windblown Sand
Akito Uchida	235	Conservation of the Engraved Rock Wall in the Temiya Cave, Japan
Nobuaki Kuchitsu *Duan Xiuye*	244	Geological Environment of the Mogao Grottoes at Dunhuang
Gerd Gudehus *Thomas Neidhart*	249	Geotechnical Stability Problems of the Dafosi Grotto
Jacques Brunet *Jean Vouvé* *Philippe Malaurent*	259	KEYNOTE ADDRESS Conservation of Subterranean Historic and Prehistoric Monuments *The Importance of the Environment and Microclimate*
Christos S. Christoforou *Lynn G. Salmon* *Glen R. Cass*	270	Deposition of Atmospheric Particles within the Yungang Grottoes
Christos S. Christoforou *Lynn G. Salmon* *Timothy J. Gerk* *Glen R. Cass*	279	Control of Particle Deposition within the Yungang Grottoes
Sadatoshi Miura *Tadateru Nishiura* *Zhang Yongjun* *Wang Baoyi* *Li Shi*	294	Microclimate of Cave Temples 53 and 194, Mogao Grottoes
Shin Maekawa *Zhang Yongjun* *Wang Baoyi* *Fu Wenli* *Xue Ping*	301	Environmental Monitoring at the Mogao Grottoes
Zhong Shihang *Huang Kezhong*	314	A Nondestructive Method for Determining Weathering and Consolidation of Stone

He Ling
Ma Tao
Rolf Snethlage
Eberhard Wendler
320 Investigations of the Deterioration and Conservation of the Dafosi Grotto

Nobuaki Kuchitsu
Duan Xiuye
Chie Sano
Guo Hong
Li Jun
329 Color Change of Pigments in the Mogao Grottoes of Dunhuang

Ian N. M. Wainwright
Elizabeth A. Moffatt
P. Jane Sirois
Gregory S. Young
334 Analysis of Wall Painting Fragments from the Mogao and the Bingling Temple Grottoes

Michael R. Schilling
Li Jun
Li Tie Chao
Guo Hong
Li Zuixiong
Duan Xu Xe
341 Color Measurement at the Mogao Grottoes

Francesca Piqué
348 Scientific Examination of the Sculptural Polychromy of Cave 6 at Yungang

Zhou Guoxin
Zhang Jianquan
Cheng Huaiwan
362 Pigment Analysis of Polychrome Statuary and Wall Paintings of the Tiantishan Grottoes

Robert H. Brill
Csilla Felker-Dennis
Hiroshi Shirahata
Emile C. Joel
369 Lead Isotope Analyses of Some Chinese and Central Asian Pigments

Hans G. Wiedemann
Gerhard Bayer
379 Formation and Stability of Chinese Barium Copper–Silicate Pigments

Wu Y. Onggi
Zhou Tie
Zhang Zhijun
Erwin Emmerling
Cristina Thieme
388 The Polychrome Terra-cotta Army of the First Emperor Qin Shi Huang

395 Contributors

404 Illustration Credits

Foreword

THE GETTY CONSERVATION INSTITUTE is committed to the preservation of the world's cultural heritage and, as such, seeks to find ways to enhance the knowledge and information available to conservation professionals as well as to a broader audience. These proceedings are part of that commitment. They have been long in the making, but waiting for them has been worthwhile.

The International Conference on the Conservation of Ancient Sites on the Silk Road, sponsored by the Getty Conservation Institute together with China's Dunhuang Academy and State Bureau of Cultural Relics, took place in October 1993 at the Mogao grottoes, Dunhuang, the People's Republic of China. Since then, several other meetings have been held. They all shared in the objectives of the initial conference: to bring together an international panel of specialists from a wide range of disciplines to provide a critical mass of expertise that would or could be applied to solving the difficult and numerous problems that threaten some of the world's most imposing and important cultural heritage sites, the magnificent Buddhist grottoes on the Silk Road.

Grottoes pose particularly thorny problems for conservation. They require a fundamentally holistic view if the conservation approach is going to be valuable in the long term. At the same time—because of their magnitude, geographic location, richness and variety of materials, unique microclimates, continuing use as religious sites, and growing attraction for tourists—the Buddhist grottoes of the Silk Road require dedicated study with a variety of disciplines to understand their deterioration problems and appropriate methods of prevention.

The conference on which these proceedings are based marked the first time that scholars and scientists from the West and China had convened at a heritage site in China for the common purpose of providing information, exchanging ideas, and devising mechanisms to save grotto sites. The essays assembled here represent contributions from Australia, Canada, France, Germany, India, Japan, Singapore, Sri Lanka, Switzerland, and the United Kingdom, as well as China and the United States. They cover such topics as site management, microclimatological analysis and evaluation, and geotechnical and environmental concerns, and provide views on a range of conservation issues that convey some of the excitement of the conference itself.

Special thanks are due to Neville Agnew who has toiled long and hard over this publication. His organizational efforts for the conference were only the first steps down the road leading to these proceedings. His attention to detail and seriousness of purpose exemplify his profound interest in the conservation of these sites as well as others around the world. It is our hope that, through this publication, the reader will gain not only insight into the scientific and technical aspects of conservation but admiration as well for the wonderful history and art of the ancient sites on the Silk Road.

Miguel Angel Corzo
Director, The Getty Conservation Institute

Preface

The genius of ancient china is remarkable and unparalleled. For three thousand years it was the undisputed master of invention and discovery—achievements well documented by Joseph Needham, the West's foremost scholar of Chinese science, in his definitive work, *Science and Civilization in China*. Consider the chemical arts of ancient China, for example; they have had a profound influence on the world. In Chinese, the word for chemistry is *hua xue*, which literally means "the study of change." This is particularly apropos in view of the work being done at sites like Mogao and others on the Silk Road. To study change is indeed necessary if we are to understand it. As custodians of the cultural heritage, our common purpose is to study the changes and deterioration affecting the physical fabric, paintings, and sculptures of Mogao and other sites throughout the world, and then to try to slow or even prevent these changes through harnessing modern chemistry and science in the service of conservation.

The West owes its knowledge of the metallurgical arts and the manufacturing processes for paper, salt, wine, porcelain, and, above all, silk, to ancient Chinese alchemy (or, as we would call it today, applied chemistry). Many of these empirical discoveries date from the last half of the second millennium B.C.E. in northern China.

Ancient Chinese technology was philosophical in nature rather than scientific, like the old Chinese theory of medicine. It is a remarkable achievement that the technological sophistication of ancient China—without the benefit of modern scientific theory—remains unsurpassed today. Who can fail to be awed by the artistic beauty and technical perfection of a bronze vessel of the Eastern Zhou (late sixth to late third century B.C.E.) or the serene splendor of the art of the Tang dynasty?

The technical inventions of ancient China were created through innate ability and industry to improve the human lot and beautify life. They are too numerous to elaborate completely; here is but a partial list:

- **Metal**. Smelting, purification, alloying, casting, and forging of all the important metals (copper, iron, zinc, lead, tin, silver, gold, mercury) date as far back as the time of the Warring States (481–255 B.C.E.).

- **Ceramics**. The making of pottery commenced very early in human history. China, however, was producing porcelain—that most precious of ceramics—by the time of the Han dynasty (206 B.C.E.–220 C.E.), a feat that baffled Europe for the next one and a half millennia. Interestingly, glass glaze for porcelain was introduced to the Han dynasty from Rome.
- **Gunpowder**. In its earliest forms, gunpowder seems to have been known in China for some two thousand years. By the Sui dynasty (581–618 C.E.), fireworks had been developed as well as instruments of war. Indeed, the world's oldest pictures of a gun come from the Mogao grottoes of Dunhuang, in a detail from a painted silk banner of the mid-tenth century (now in the Musée Guimet, Paris).
- **Lacquerware**. This goes back into Chinese legend.
- **Colors and Dyes**. Ancient Chinese writing does not fade because the principal materials are carbon (lampblack) and glue. Western ink, being iron based, is not as permanent. The natural dyes, such as indigo and saffron, were known since antiquity in China.
- **Zero**. We take the concept of zero for granted, but its invention was of the utmost importance in history; it is essential for carrying out mathematical computation. Mathematicians in China may have used the zero before those in India.
- **Silk**. The Romans believed that silk grew on trees (Pliny and Virgil). The Chinese, who had discovered its secret a thousand years earlier, had no intention of dispelling the myth, as they maintained a monopoly on the trade. So great was the Roman lust for silk that, by 380 C.E., its high cost began to have a serious impact on the economy of the empire.

Although the Silk Road is one of the oldest of the world's great trade routes, it acquired this name only in the last century, as Peter Hopkirk points out in his book, *Foreign Devils on the Silk Road*. The term, coined in the last century by Baron Ferdinand von Richthofen, is misleading because the Silk Road consists of a number of caravan routes across China, Central Asia, and the Middle East. It carried a great deal more than silk and was traveled in both directions. China-bound caravans, for example, carried gold and metals, wool and linen, ivory, coral, and glass. Many items were bartered or sold on the way. Parthian middlemen controlled the route beyond China, so Chinese merchants were never seen in Rome. Recent archaeological evidence suggests that trade along the Silk Road was conducted even earlier than believed. John Noble Wilford reported in the *New York Times* in 1993 that strands of silk had been found in the hair of an Egyptian mummy dating from about 1000 B.C.E. This is long before regular traffic began on the fabled trade route, and a thousand years before silk was thought to have been used in Egypt.

More than goods were traded via the Silk Road; more important in many ways was the cultural exchange of ideas, religious beliefs, language, and thought—evidence of which are to be found at Dunhuang, the eastern hub of the great route and a gateway to China. It is for this reason that the conference

was held at the Mogao grottoes: to exchange information and ideas—to trade, as in days of old, knowledge for the common good of humanity's cultural heritage.

The Getty Conservation Institute has been working in China with the State Bureau of Cultural Relics at the two great sites of the Mogao and the Yungang grottoes. Why should the Getty Trust, a private foundation, be undertaking conservation in China, especially since none of the programs at the Getty collects Asian art or has a specialized interest in it? The answer is found in the philosophical ethic that guides the Getty Conservation Institute in its mandate and mission of preservation of the cultural heritage.

The world's cultural heritage reflects the achievements of humanity since the dawn of civilization. Cultural heritage is essential to the understanding of history and of the forces that create contemporary societies. It is a living source of our identity and an expression of our spirit as it unfolds through time. Cultural heritage transcends temporal and geographic boundaries; it offers a sense of continuity in a rapidly changing world and connection with other societies, past and present.

Today, cultural heritage is threatened as never before. Technological innovations and the global population explosion have given rise to unchecked development, industrial pollution, increased tourism, rapid obsolescence, and increasingly destructive methods of warfare. As a result, the store of material evidence of our past is vanishing at an ever-accelerating rate.

We recognize the importance of development and acknowledge that preservation efforts must take place within a framework of the evolution of today's societies. Yet the physical remains of the world's cultural heritage are irreplaceable. They must be protected and managed effectively for present and future generations. To achieve a balance between these concerns, considered choices must be made to save the cultural heritage. The significance of the sites and objects we seek to preserve must be understood; we must ask for whom are they important and why. Responses appropriate to the historic cultural context of the materials must be developed.

Conservation is a science, an art, and a craft. Beyond that, it is a concept that needs to be encouraged and fostered as a part of our way of life. Conservation is the means whereby the survival of the cultural heritage—which defines the image of humanity—is ensured, now and in the future. Conservation, as the custodian and preserver of the earth's artistic and historic legacy, must shape the ethic of humanity.

The Getty Conservation Institute has worked in China with the State Bureau of Cultural Relics and with the site authorities at Mogao and Yungang to promote the preservation of the grottoes through site-conservation measures and an intensive site-management training course, as well as through scientific analysis and training, the introduction of new conservation materials and techniques, pollution studies, environmental monitoring inside and outside the grottoes, discussions, and professional contacts. Throughout this work, we have collectively taken the broad picture by looking at the most severe threats to the sites and by considering their real needs.

In addition to being a conference record, these proceedings celebrate the fiftieth anniversary of the founding of the Dunhuang Academy. They also

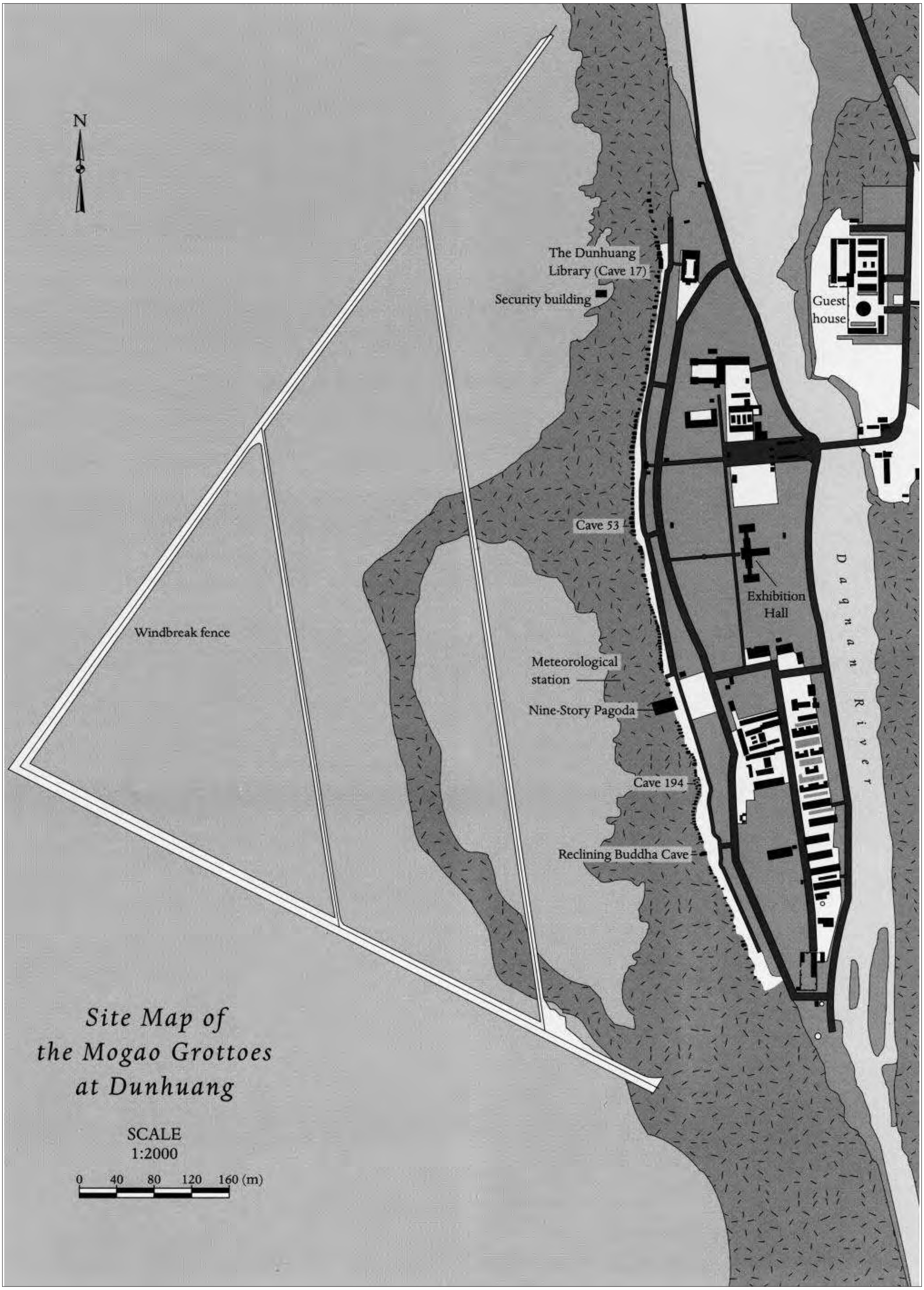
pay tribute to director Duan Wenjie and his life of dedication to the study and preservation of *Mogaoku*—the "great art gallery in the desert," as the site has been called.

This conference was a success because of the outstanding contributions of many people. In particular, I extend sincere appreciation and thanks to our esteemed colleagues Director Zhang Deqin and Deputy Director Zhang Bai from the State Bureau of Cultural Relics. Along with their predecessor, Shen Zhu, they have been unfailingly supportive of our collaboration. Thanks also to Kwo-Ling Chyi, Joan W. Shi, Sara Tucker, and Jeffrey Riegel for assisting with interpretation; and Chen Shiliang, Lin Hongliang, Jeffrey Riegel, and Zhang Yuzhong for presenting lectures during the post-conference tour. In the organization of the conference, we have enjoyed full partnership and collaboration of the Dunhuang Academy guided by Deputy Director Fan Jinshi and her excellent staff.

In the preparation of these proceedings for publication, appreciation is extended to Dinah Berland of the Getty Conservation Institute for managing the editorial production of the publication and editing many of the texts, Jeffrey Cohen of Getty Trust Publications for designing the series, and Hespenheide Design for typesetting and layout of this volume. Thanks also to GCI staff Sara Tucker, Shin Maekawa, Michael Schilling, and Francesca Piqué, and to consultant Po-Ming Lin, for preliminary review of the proceedings; to Lin for coordinating the articles of the authors in China and, with Kwo-Ling Chyi and Charles Ridley, translating the Chinese texts; to Keith Eirinberg and Elizabeth Maggio for copyediting the articles; to Joy Hartnett for editorial assistance and research; to Scott Patrick Wagner and Alison Dalgity for helping with desktop production; to Desne Border for proofreading; and to Anita Keys for coordinating the book's production.

Lastly, I offer a tribute to Huang Kezhong, a fine colleague and friend, who enjoys a special place in the hearts of GCI staff members who traveled with him across China on innumerable occasions by plane, by train, and—on one trip indelibly engraved in our minds—by bus for twenty-four hours in snow and dust storms. The Getty Conservation Institute is proud to be associated with these projects in China and is privileged to have met fine people who are now called friends.

Neville Agnew
Associate Director, Programs
The Getty Conservation Institute


N
The Dunhuang Library (Cave 17)
Security building
Guest house
Cave 53
Exhibition Hall
Daqnan River
Windbreak fence
Meteorological station
Nine-Story Pagoda
Cave 194
Reclining Buddha Cave
Site Map of the Mogao Grottoes at Dunhuang
SCALE
1:2000
0 40 80 120 160 (m)

Novosibirsk
RUSSIA
KAZAKHSTAN
MONGOLIA
Urumqi
Kizil grottoes
Anxi
Yulin grottoes
Dunhuang
Yumen
Mogao grottoes
Jia Yuguan
Jiuquan
UZBEKISTAN
KYRGYZSTAN
TAJIKISTAN
Takla Makan desert
Tiantishan grottoes
Gulang
Lanzhou
Bamian
Kabul
Herat
Ghazni
Taxila
AFGHANISTAN
CHINA
Leshan
New Delhi
PAKISTAN
NEPAL
Kathmandu
BHUTAN
Mekong River
INDIA
Calcutta
MYANMAR
Pak Ou
Tam Ting caves,
Luang Prabang
LAO PEOPLE'S DEMOCRATIC REPUBLIC
Ajanta
Ellora
Aurangabad
BANGLADESH
Mumbai
Arabian Sea
Bay of Bengal
THAILAND
Bangkok
KAMPUCHEA
Angkor
Phnom Penh
Andaman Sea
Gulf of Thailand
N
Anuradhapura
Sigirya
Polonnaruwa
Dambulla
SRI LANKA
Indian Ocean
MALAYSIA

Sea of
Okhotsk
Aihui (Heihe)
Baicheng
Tianshan
Temiya cave
Sea of Japan
Yungang grottoes
Datong
Beijing
NORTH KOREA
Dafosi
grottoes
Yuncheng
Binxian
Xian
Maijishan grottoes
SOUTH KOREA
JAPAN
East China
Sea
Pacific
Ocean
Pingchang
Hetian
TAIWAN
Philippine Sea
South
China Sea
VIETNAM
PHILIPPINES
Ho Chi Minh City
(Saigon)
0 200 400 600 800 1000
KILOMETERS
BRUNEI
MALAYSIA

China Dynasty Table

Xia	ca. 21st century–16th century B.C.E.
Shang	ca. 16th century–11th century B.C.E.
Western Zhou	ca. 11th century–770 B.C.E.
Eastern Zhou	
Spring and Autumn Period	770–476 B.C.E.
Warring States Period	475–221 B.C.E.
Qin	221–207 B.C.E.
Western Han	206 B.C.E.–24 C.E.
Eastern Han	25–220
Three Kingdoms	220–280
Wei	220–265
Shu	221–263
Wu	222–280
Western Jin	265–316
Eastern Jin	317–420
Southern and Northern Dynasties	420–589
Sui	581–618
Tang	618–907
Five Dynasties and Ten Kingdoms	907–979
Song	960–1279
Northern Song	960–1127
Southern Song	1127–1279
Liao	916–1125
Jin	1115–1234
Yuan	1271–1368
Ming	1368–1644
Qing	1644–1911
Republic of China	1912–1949
People's Republic of China	1949

Dunhuang Art: The Treasure of the Silk Road

Duan Wenjie

The ancient caravan route linking China with the West is known as the Silk Road, a great conduit of commercial and cultural exchange stretching 7,500 km from Chang´an (present-day Xian) to Rome. Chinese silk, which gave the route its name, was transported to the West, while wool, dyestuffs, gold, and silver—along with cultural ideals—traveled east. Among these, the religious culture of Buddhism left a lasting and profound mark on China. Under the open-door policy of Tang dynasty Emperor Li Shih-min, the Silk Road flourished as a meeting ground between East and West during the great era of the Tang civilization (618–907 C.E.), when Chinese feudal culture reached its height and spread its influence throughout the world.

Dunhuang is strategically located at the far western limit of early Chinese settlement, at the point where the two branches of the Silk Road converge. It was the first trading town reached by foreign merchants entering Chinese territory from the west and thus became the repository for a cultural exchange that encompassed the art, literature, and religions of China, Central Asia, and the West. This vigorous meeting of cultures produced a wealth of art and artifacts at various points along the Silk Road, especially at those towns where Buddhist monks stopped off on their pilgrimages to India. Dunhuang was the last stop in China on the great pilgrim route. On the cliff face above the river they excavated cave temples, or grottoes, to serve as lodging, as centers of worship, and as repositories for documents, sacred works, and works of art. Because of its strategic location, the grottoes of Dunhuang came to be the largest and greatest of the Buddhist grotto complexes along the Silk Road, with a history spanning one thousand years. As such, Dunhuang can be seen as a microcosm of Chinese medieval culture, reflecting the broad multinational, multiethnic influences that gave it such distinctive character.

During its height, Dunhuang culture gave rise to a wealth of architecture, sculpture, murals, paintings on silk, calligraphy, wood-block prints, embroidery, literature, music, opera, and other art forms. Although the contents of the library cave have unfortunately been dispersed to museums in the West, the grottoes still contain a trove of paintings and statuary that exemplify religious and historical themes and artistic

techniques as they evolved over a one-thousand-year period of Chinese art. The murals, covering 45,000 m^2, fall into the following categories:

- revered images: images of each of the divinities worshiped in Buddhist temples; these murals are the most numerous and are executed with the highest degree of artistic skill;
- Buddhist scriptural tales: (1) stories of the life of the Buddha, (2) stories of previous lives, and (3) karmic stories; these murals draw the viewer into their fantastic realm;
- Chinese mythical themes: images of the creator Fuxi, the creatrix Nuwa, the Royal Sire of the East, the Queen Mother of the West, the Vermilion Bird of the South, the Dusky Warrior of the North; these figures, along with other deities, have entered the cave art;
- images evolved from sutras: large-scale murals depicting the Buddhist utopia, a world of great joy and splendor;
- Buddhist history: these murals combine historical figures with Buddhist tales, including stories from India and Central Asia, as well as Zhangye, Jiuquan, and other locales;
- portraits of donors: images of those who funded the grottoes, murals, and sculptures—among them, portraits of individuals from every social class and ethnic group, as well as merchants of various nationalities; and
- ornamentation: geometrical patterns depicting plants, animals, heavenly bodies, and people in ornamental design.

The mural art of Dunhuang reflects the daily life of medieval Chinese of all classes, as well as that of people from countries throughout Asia. Noteworthy are scenes of the manufacture of goods, social life, the commercial trade between China and the West, the meetings of princes, the succession of Chinese emperors, the worship of the Buddha at Turfan, the travels of the Princess of Huige, and more. The mural art of Dunhuang is a mirror of Chinese history, described by one specialist as a library contained in wall paintings. The art of Dunhuang has added inestimably to our understanding of medieval life in China.

The murals, sculpture, and architecture of the grottoes also illustrate the ways in which grotto art originating in India was adapted under Chinese influence. Departing from the Indian model, the Chinese introduced wooden architectural structures to achieve the effect of an audience hall of a Chinese palace. Moreover, Chinese mythical themes were incorporated into the decorative patterns, enriching their content and adding to their scope. As the Indian Buddhist tales were illustrated with Chinese characters, clothing, and customs, a hybrid was created that exemplified the exchange and merging of cultures through which the arts flowered.

Following the traditions of the Han and Jin dynasties, the artists of Dunhuang combined realism with imagination, achieving an expressive quality by outlining figures and features, which were then filled in with color. Using this uniquely Chinese method, the artists of Dunhuang put

their imprint on the Indian Buddhist subject matter. Moreover, they absorbed and adapted expressive techniques and themes introduced from the Persian and Greek, as well as Indian, heritage—e.g., the portrayal of the beauty of the human figure or characteristic styles for depicting divine images.

Ultimately, the creative blending of themes and artistic techniques established a new Chinese style of Buddhist art; by the fifth century c.e., the style had itself become a source of influence on Western, Central Asian, and Indian culture.

The grottoes of Dunhuang, in which history is crystallized, has been listed by Unesco as a World Heritage Site. The mission of the Dunhuang Academy is to preserve, study, and promote the site. The task of preservation—the Dunhuang Academy's first priority—has been advanced greatly by domestic and international cooperation in recent years, the evidence of which was borne out by this conference.

Acknowledgments

On behalf of the Dunhuang Academy, the author extends gratitude to all individuals and institutions who have contributed to the study and preservation of the site.

An Overview of Protection of Grottoes in China

Huang Kezhong

Most of China's grottoes are rock-cave temples, which served as centers for Buddhist worship after Buddhism spread eastward from its roots in India. The earliest grottoes date back to the second century C.E., during the Han dynasty. The major excavation period occurred from the fourth to the ninth century, during the Northern Wei, Sui, and Tang dynasties. While most of the grottoes were completed during this period, excavation continued into the Ming and Qing dynasties.

The grottoes are concentrated at sites along the ancient Silk Road and the Yellow River and Tangtze River basins. The best-known sites include the Mogao grottoes at Dunhuang in Gansu Province; the Yungang grottoes at Datong in Shanxi Province; the Longmen grottoes at Luoyang in Henan Province; the Maijishan grottoes at Tianshui in Gansu; the Buddha cliff statue at Dazu in Sichuan; the Kizil grottoes in Xinjiang; and the Yulin and Bingling grottoes, both in Gansu. The total number of grotto and cliff-statue sites nationwide exceeds 250; among these, 30 are listed as cultural relic protection sites at the national level, while 94 are listed at the provincial level and 124 at the municipal and county levels.

The grotto art—architecture, wall paintings, and sculpture—provides vivid documents for the study of China's social economy, politics, religion, art history, and architectural construction methods of the Middle Ages. Drawing on the traditions of Indian grotto art, Chinese grotto art developed under the influence of Han dynasty customs and artistic traditions. During the later phases of grotto carving, elements of Taoism and Confucianism were integrated into the dominant Buddhist imagery.

Grotto caves are typically classified according to function: tomb cave, pagoda or temple cave, lecture room cave, meditation room, monk's cell, Buddha hall. The sites can also be classified according to the properties of the rock: sandstone, conglomerate, limestone, crystalline rock. The rock body types most commonly selected for carving—conglomerate and limestone—were thick, complete, and homogeneously stratified. The preferred rock type was not too hard to be easily cut; ideally, it had an internal stability and had not undergone any tectonic changes.

The condition of the grottoes has deteriorated over the centuries due to human and natural causes such as erosion by efflorescent salts, which has led to large areas of collapse at the Mogao and Maijishan grottoes at various historical times. The Kizil grottoes remain threatened by a pattern of gullies that crisscross the top of the cliff. The Jiaoshan cliff statue, at Zhenjiang in Jiangsu Province, was severely destabilized during the torrential rains of 1990, which caused the Yangtze river to rise. Efflorescence of the statues and carvings at the Yungang grottoes and in the Bingling Temple is advancing at an alarming rate, while the granite statues in Quanzhou and in the Qingdao area near the seashore are eroding as a result of winds from the sea. Acid rain is exacerbating the efflorescence of sculptures in Dazu, Xiangtang Shan, and Siwangshan.

History of Consolidation and Restoration Efforts

Much of the key work of the last thirty years has focused on emergency repair and consolidation of grottoes located near active earthquake zones, where the threat of collapse is greatest. Much has been accomplished during this time to preserve the cultural heritage. For example, a reinforced concrete facade installed at the Mogao grottoes in the 1960s prevented the collapse of large areas and protected fragile wall paintings from exposure. The disadvantage of this consolidation structure is that its appearance is too artificial and is aesthetically unappealing. In this case, it was difficult to honor the principle of "no change of the status quo ante," as stipulated in the Cultural Relics Protection Laws.

The Maijishan grottoes, which were in an equally precarious condition, underwent consolidation in the 1970s. Over a five-year period, various approaches were tested repeatedly, including pillar supports, grouting consolidation, and protection measures against rock movements. A plan that combined grouting consolidation and crevice grouting was adopted. Although this approach was less visually intrusive than the facade at Mogao, problems remained—e.g., the cement-sprayed surface layer covered the ancient architectural pillar holes, and the concrete shell increased moisture within the rock caves. In the stabilization projects at Longmen and Yungang grottoes, chemical grouting measures were used with attention to restoring the grottoes as closely as possible to their original condition.

The restoration projects undertaken at some grottoes generated controversy. For example, at Xumishan grottoes—where the Buddha figures were exposed to sun and rain after the collapse of the rock caves—restoration of rock eaves and walls was performed in the 1980s, according to the appropriate scientific methods, as deemed necessary. However, some aspects of the restoration were not harmonious with the surroundings, and details were introduced that were not authentic. This is an area where further improvement is needed.

In recent years, the preliminary study for the maintenance of the Leshan Buddha statue examined the use of modern scientific and technological means, art historical documents, traditional and modern materials, and new techniques with the aim of providing a solid scientific foundation for the restoration of the statue.

A comparison of approaches to Chinese cultural relic protection and maintenance with international regulations, such as those spelled out in the Venice Charter, shows that most international and domestic strategies aim at minimal intervention, historical authenticity, and documentation before and after maintenance.

The formulation of a specific national cultural relics policy is especially urgent because China is not only a large country with abundant cultural relics but also a developing country with rapidly expanding capital construction. Unless protection priorities are established and laws enforced, cultural relics will be damaged by economic development. For example, in 1969 a railway was illegally constructed in the area of the fifteen-hundred-year-old Longmen grottoes. The shock of explosions during the railway construction, and vibration from the train itself, caused collapse of some caves and aggravation of water-seepage problems. The railway was eventually moved out of the protection area.

Preliminary Research

Research has focused on assessment of the value of the grottoes and their historical development, collection of records documenting the history of protection and restoration, assessment of damage, monitoring of the environment, and evaluation of construction technology and materials. This preliminary research, which has won wide attention, has brought together specialists in history, archaeology, art, architecture, engineering, the sciences, and cultural relics protection, who share a commitment to establishing a solid foundation for conservation and subsequent maintenance.

The results of the study show that damaging natural effects include water seepage and related problems caused by rainfall, river water, and underground water; instability of rock precipices; earthquakes; rock efflorescence; and erosion by wind and sand. Human factors contributing to the deterioration of grottoes include changes in the internal microclimate due to tourism; environmental pollution; local mining, which may cause ground subsidence; and shock caused by explosions.

The nature of this damage has dictated the following approaches to research:

1. Rock sculptures and geological phenomena are recorded in plane, elevation, and section drawings by using close-range photogrammetry.
2. Geological engineering mapping—which routinely records factors such as the strata, lithologic character, tectonic effects, hydrology, and physical geology—is expanded to include rock sculpture damage, crevice distribution, areas of endangered rock, salt efflorescent condition of sculpture, seepage point locations, and so on.
3. In some unstable areas, precise gauges are used to monitor crack formation.
4. Research on salt efflorescence of rock sculptures involves classification of relevant factors and long-term monitoring of

meteorological conditions as well as seepage and permeation. Using samples of profile sections of efflorescence of rock sculptures, a series of tests—chemical analysis, differential thermal analysis, X-ray diffraction analysis, spectral analysis, and scanning-electron-microscope examination—is conducted to establish the physical and mechanical properties of the rock. The results of these laboratory analyses provide the basis for conclusions concerning the nature of damage due to efflorescence. The extent of efflorescence of rock sculpture is investigated by using point-load intensity tests to obtain the tensile strength and tensile-strength index of the rock, whereas sonic wave analysis is used to indicate the efflorescent range of the surface. Efflorescence depth is studied by analysis of the resistivity of the surface of the rock sculpture; and lithofacies variation is measured by variation of the chemical elements with increasing depth.

5. Some of the geophysical exploration methods used include direct-current resistivity for exploring the seepage path and the depth of bedrock on top of the rock caves; sonic waves to measure the efflorescent range of the rock body, the location of large crevices, and the effects of chemical grouting; microbathymetry to measure the thickness of mantle rock, the direction of propagation of crevices, and the penetration depth of protective materials; and the shallow seismic method to explore crevice development in the depth of the rock body, internal defects of rock sculptures, and the archaeology of the site. A Fathometer is employed to locate the position, size, and shape of subaqueous caves under the seat of the Buddha; radar assists in identifying buried rock caves. A nuclear moisture gauge allows for nondestructive investigation of density and moisture of rock sculpture.
6. Seismographs of various kinds are used to measure the dynamic stability of grottoes with respect to nearby explosions and locomotive and motor vehicle vibration. Natural seismic investigation can be conducted on the rock caves to assess the effects of seismicity on the caves.
7. For the assessment of environmental geology of rock caves excavated (as most were) on precipitous slopes, the three-dimensional, finite-element method is used to calculate rock body stability. In order to establish a structural model of the rock body, the joint fissures are measured to provide a basis for analyzing permeation channels and their paths. Statistical analysis can be undertaken on geometric parameters of the structural planes. A picture of the network of structural planes of the rock body and the connected network system can be obtained by setting up a probability model and conducting computer simulation on the structural plane network. These data then provide the foundation for rock body stability

analysis, identification of permeation channels, and treatment of seepage.

Environmental monitoring has been designed to address specific problems, such as dust and harmful gases containing SO_2 and NO_x that are emitted from cement factories, power plants, and lime mines in the neighborhood of the South and North Xiangtang Shan grottoes at Handan, Hebei Province. A project for monitoring hydrology and underground water was established at Longmen grottoes, where the drying up of springwater and declines in the flood-discharge capacities of rivers are posing a threat to the safety of the grottoes. At the Mogao and Yungang grottoes, large-scale monitoring efforts—undertaken jointly by the Dunhuang Academy, the Yungang Grottoes Management Institute, the Chinese National Institute of Cultural Property, and the Getty Conservation Institute—have focused on sand flow and coal dust pollution.

Further preliminary research has been conducted to establish the feasibility of a consolidation and maintenance plan for the rock caves and to evaluate consolidation materials. At the Yulin grottoes, for example, a method of bolting and chemical grouting was tested to establish whether the grouting material can form pores inside the conglomerate layer. From tests conducted on consolidation materials, including bolt grouting, crevice grouting, and anti-efflorescent coatings for rock surfaces, good results were obtained on inorganic grouting material used for grouting crevices under humid conditions, and antiweathering polymeric material for rock sculptures.

Approaches to the Protection and Maintenance of Grottoes

Vestiges of traditional protection and maintenance measures left over from successive dynasties remain functional at many of the grottoes. Eaves and doors were constructed to protect sculptures from exposure to rain and sun, as can be seen today in the Tang dynasty shelters at Longmen grottoes. Drainage systems were also installed at many sites, such as the combination of open channel and underground drainage devised to protect the rock sculpture at the Dazu grottoes. At the Kizil grottoes, mortar and wooden bolts were used to reinforce the cave face and precipitous slope. These are just a few of the many examples of historical protection efforts devised.

Modern approaches draw on traditional technology while also incorporating new materials and techniques. A key focus today is on protecting grottoes from various types of erosion by water. For example, drainage systems can be installed on top of caves to prevent seepage of surface water. Groundwater drainage can be constructed in front of the caves; by lowering the underground water level, moisture and dew inside the caves is reduced or eliminated. The construction of eaves protects the carved rock from damage due to direct sunlight, sand, and acid dust; the eaves also help to moderate humidity changes.

Historically, concrete retaining walls were constructed to address the problem of collapse or slippage of the rock body of the caves. These

methods are not used today because they are visually intrusive and mar the original historical features of the site. Instead, bolt-grouting is used for reinforcing areas with crevices and dense concentrations of caves. Although the bolt-grouting method represents an improvement, it, too, partially alters the features of the caves and obscures some historical traces. The reinforced steel net shield method has recently been replaced by chemical coating materials.

Another approach to treating fractures in carved stone, fissures in precipice walls, and collapse is by grouting adhesion. The preferred grouting materials are acrylic ester, epoxy resin, and inorganic chemical materials, which approximate the physical and mechanical properties of the rock. These materials are durable, resistant to cold, waterproof, and easy to apply; they achieve a solid bond; and they solidify at room temperature. Nondestructive sonic measures are used to examine indicators of the grouting effectiveness, such as depth, range, rock body density, and deformation.

For relatively well-preserved carved rock, with only slight efflorescence, protective measures focus on limiting potentially harmful environmental factors. Protective coatings are applied directly to stone statuary only in cases where severe efflorescence threatens the statues with complete collapse. Any plan for applying such coatings should identify the relevant efflorescent agents and the performance parameters of the coating material—e.g., transparency, absence of color, good chemical stability, good penetration, solidification strength, and antiflaking and antiglare properties. Preferred coating materials currently used are high-molecular organic polymer materials such as organosilicones, methyl methacrylate, and polyurethane. Some inorganic materials that are being successfully used are high-modulus potassium silicate and various compound materials.

Laboratory tests have been conducted on the properties of these materials to evaluate variations along the direction of depth, as well as pore ratio, permeability to water vapor, compressive and tensile strength, and erosion resistance. Materials testing has also investigated surface hygroscopic coefficient, capillary hygroscopic coefficient, maximum hygroscopic rate, permeability, antiaging properties, resistance to heat and cold, mechanical and chemical stability, recoating performance, and other parameters. Long-term field monitoring stations have been established to maintain ongoing evaluation.

Discussion

Three considerations remain for discussion: laws and public policy regarding protection of the grottoes; the controversies surrounding the principle of "no change of the status quo ante"; and the combination of traditional techniques and materials with modern consolidation measures.

The point has been made previously in this paper that the development of modern industry, capital construction, the tourist industry, environmental pollution, and the changing microclimate in the area of the grottoes have accelerated the deterioration of the rock caves to an alarming degree. The work of conservation specialists alone cannot remedy these problems. Cooperation is needed from all sectors of society,

particularly from government at all levels in the establishment and implementation of laws for the protection of cultural relics.

The agenda for conservation organizations is to define the grottoes' protection area, specifying the key protection area, general protection area, and limited construction zone. Moreover, environmental protection regulations must be established, with administrative departments overseeing construction and environmental protection. Long-term environmental monitoring stations have been established in severely polluted grotto areas to identify the major causes of pollution. Data gathered from these stations provide the basis for developing criteria for levels of harmful substances in the atmosphere surrounding the site.

It is likewise essential to limit the construction of new factories and other sources of pollutants in the protection area, while also monitoring pollution from newly enlarged enterprises. Reasonable pollution-treatment regulations must be formulated, along with a plan for managing sources of pollution. Further research on the appropriate environment for grottoes must include assessment of temperature, humidity, and control of visitors.

In planning the maintenance and consolidation of grottoes, it is important to be prudent in interpreting the principle of "no change of status quo ante." Many cases present ambiguities that cannot be decided on the basis of this principle alone. For example, the construction of facades on eaves on the cliff face has aroused controversy because they alter the original features of the grottoes. Yet, in some cases, such architectural interventions are necessary to protect fragile statuary from airborne dust and from sudden changes in temperature or humidity that accelerate the weathering process. Also, the metal frame type of shelter, fitted with lightweight synthetic textile net, provides effective control of the microclimate but has a disharmonious appearance.

The restoration of the Leshan Buddha is another problematic case. Maintenance undertaken in the 1960s altered the Buddha's original features—nose, eyes, mouth, and lower jaw—in significant ways, and therefore restoration is indicated. But, the question is, to which historical period should it be restored? Photos of the Buddha taken during the period of the Republic of China show the figure to be inaccurately restored, while documents from the Qing dynasty period show the figure to be severely damaged, with many cavities on the face. In view of this situation, according to the restoration principle, it is better not to restore the Buddha.

In the 1970s, the severely damaged waist of the open-air Buddha statue in Cave 20 at Yungang was restored with a rock material similar to the original. In the past, Chinese restoration specialists have advocated mixing the spurious with the genuine, so afterwards viewers cannot tell which part of the statue has undergone restoration. However, many international cultural relic protection specialists believe, to the contrary, that newly added parts must be clearly defined. At present, the majority view here is that restored parts of cultural relics should not be strikingly visible when viewed at a distance, though some difference may be noted close up.

Evidence of the statue quo ante must be obtained prior to restoration, to be followed by detailed recording and documentation.

There is much to value in traditional maintenance technology—e.g., the drainage and antiseepage systems, shelters and eaves, the principle of minimal intervention, and use of original material to maintain style and structure. Some traditional measures can be discarded, such as the use of gold size on the surface of the carved rock, which caused erosion by trapping moisture, or the use of iron rods as reinforcement, which ultimately caused fissures when the rods rusted. The use of new materials and technology must, above all, preserve the effects of the status quo ante; and they must be reversible so later generations can replace them with even more effective consolidation measures.

Fifty Years of Protection of the Dunhuang Grottoes

Fan Jinshi

The grottoes in the Dunhuang area comprise the Mogao grottoes, the West Thousand Buddha (Xiqianfo) caves, and the Yulin grottoes near Anxi. Like a great many of the grottoes of China, these are Buddhist temples that were cut into cliffs along river banks. The Daquan River flows past the front of the grottoes.

The Dunhuang grottoes were carved into a conglomerate of the Quaternary Jiuquan system. Because the loose conglomerate rock was not suitable for fine carving, murals and clay-plastered polychrome statues were produced to depict the concepts of Buddhism. Each cave contains a combination of polychrome sculptures, murals, and architectural structures. These artworks were made over a thousand-year period from the fourth to the fourteenth century, when Dunhuang was a sacred center of Buddhism. Among the three grotto sites, 549 caves contain wall paintings and painted sculptures, and more than 250 caves contain other forms of art (Dunhuang Cultural Relics Research Institution; Li Yongning 1981, 1982). Altogether, these sites are of extraordinary artistic, historical, technological, and economic value. The Mogao grottoes in particular are one of the world's most famous large-scale cultural heritage sites. After fifteen centuries, some of the rock temples of the Dunhuang grottoes have undergone severe damage due to historical and natural causes. The cliff rock has fractured, sculptures have fallen over, and paintings have been damaged by flaking, peeling, and salt efflorescence (Fan 1993).

In January 1944, the Dunhuang National Art Research Institute was established by the Chinese government, initiating a new stage in the preservation of ancient relics. Since the 1950s, extensive emergency repairs have been carried out and scientific techniques of preservation applied.

The Pioneering Years (1943–50)

Fifty years ago, in the midst of China's war with Japan, some ten staff members of the Dunhuang National Art Research Institute began the work of preserving the grottoes under the leadership of Chang Shuhong, the institute's director at the time. Conditions were difficult due to limited financial support, lack of equipment, and the remote, windy, and sandy

environment of China's northwestern frontier. Yet the team accomplished a tremendous amount of work. They constructed an enclosing fence 850 m long to control visitors, connected several caves with walkways, removed sand that had accumulated inside more than three hundred grottoes, removed the clay beds built by Russian refugees who had occupied the caves in 1921, made preliminary renovations, and installed wooden windows and doors in some of the rock temples to protect the artwork from human damage and erosion by blowing sand. In the course of this work, they also discovered six more caves and more than three hundred scrolls of sutras (Dunhuang Cultural Relics Research Institution 1977). For the purpose of site management, they supplemented and developed a new cave-numbering system based on an existing one, made an inventory of the grottoes' contents, produced a written description of the site, organized exhibitions, instituted guided tours, and arranged for security guards to be responsible for the safety of the grottoes. All of these efforts formed the initial framework for the present program of site protection, research, and presentation. All of the protection measures at that time were rudimentary to some degree. Nevertheless, they effectively prevented looting and vandalism of the caves. The eight years of hard work by these pioneers brought to light once more the importance of these cultural treasures to the heritage of the world.

Remedial Conservation Period (1950–80)

Although much work was accomplished during the previous period, deterioration due to either natural or human causes had yet to be addressed. Destabilization of the cliffs, salt efflorescence on the paintings and statues, and deterioration of the roofs of certain caves were advancing at an alarming rate.

In 1950, the Dunhuang National Art Research Institute was reorganized as the Dunhuang Cultural Relics Research Institution (now the Dunhuang Academy), and the first site-management department was founded. A series of comprehensive surveys was carried out to evaluate the impact of the natural environment on the grottoes, the deterioration of the caves and cliffs, features of the architecture, and the condition of existing wooden structures. On the basis of this survey, a comprehensive, full-scale renovation of the Mogao grottoes was begun in 1951.

At that time in China, traditional technology and craftsmanship were being revived. Earlier techniques were thus applied to the restoration of the damaged caves, the removal and replacement of components, the substitution of materials, and the restoration of fallen structures. Five Song dynasty wooden facades of Mogao caves 427, 431, 435, 437, and 444 were replaced and restored to their original shape (Zhao 1955). Rotten wood frames within some statues were replaced, and tilted statues were straightened. Clay was applied to the edges of wall paintings that had separated from the wall, and the paintings were secured with anchor pins and the application of grouting to effectively prevent further detachment. In 1965, experimental reinforcement work on the cliff face was carried out to reinforce a 200 m long middle section of the southern caves 232–260, using

columns of rock construction and wooden planks. Stabilization of the precarious cliff face, made fragile over the centuries by extensive excavation of the caves in weak strata, was carried out from 1963 to 1966. Stone pillars were used to support overhanging rock at the top of the cliff face, and retaining walls were built to prevent block failure around the crevices. This project resulted in reinforcement of more than 570 m of the cliff face and 358 caves. At the same time, the walkways between caves of the same or different levels were connected, permitting access to several hard-to-reach caves while retaining the simplicity of their external appearance. With available technology, this million-yuan project resulted in the effective reinforcement of the southern portion of the Mogao grottoes to the greatest extent possible (Sun 1994).

Meanwhile, the most recent scientific technology began to be incorporated into the conservation work at Mogao. For example, testing of and experiments on the conglomerate using polymer materials (polyvinyl alcohol and polyvinyl acetate solutions) as adhesives led to the restoration of some of the previously untreatable flaking and salt efflorescence of the wall paintings (Li Yunhe 1993a). To prevent abrasion by windblown sand, experiments were conducted using grass barriers and windbreak fences (Ling 1993). Studies on the techniques of removing and transferring wall paintings were also conducted (Li Yunhe 1993b). The purposes of these studies were to expose the hidden wall paintings and to install paintings that had been removed from remote, endangered sites.

For the long-term protection of grottos from damage by natural processes and human factors while the caves were in use, we took the following remedial measures:

1. Following the ancient practice of building shelters outside and laying floor tiles inside the caves, doors and cement floors were installed in some caves to prevent abrasion from windblown sand and damage due to sunlight, dust, and visitors.
2. Sand and dust that had accumulated in front of and inside the caves were removed to prevent it from further entering the caves and damaging the wall paintings.
3. Weather stations were set up to monitor the environmental patterns around the Mogao grottoes (Sun 1993).
4. Descriptive pamphlets were published and explanatory plaques installed around the grotto site. Visitor regulations were drawn up and tour guides provided to explain the site to the visitors, monitor their conduct, and keep them from damaging the caves.
5. A system of regular grotto inspection was established to detect any damage caused by natural processes or human factors and to facilitate immediate emergency repairs to damaged caves.

Many national laws and regulations regarding the protection of cultural relics, including grotto sites, were formulated and promulgated before the 1960s. They included provisional management regulations and

procedures, a list of major cultural sites, and temporary procedures for the repair and management of ancient buildings and cave temples. According to the Law and Regulations on Cultural Relics, the Dunhuang grottoes—including the Mogao grottoes, the West Thousand Buddha caves, and the Yulin grottoes—were listed as key national cultural protection sites. The establishment of these laws not only raised the prestige of the Dunhuang grottoes and resulted in society regarding them with greater importance but also put them under legal protection, which promoted and assisted in their conservation.

Renovation at this time consisted of a full-scale emergency repair to save and preserve those caves that were on the verge of collapse, as well as damaged wall paintings and statues. The data gathered during this first stage provided the foundation for identifying and achieving a preliminary understanding of the types of damage present. The conservation and management experience obtained during this period also helped those involved to develop a functional management plan. All these factors served to establish a good basis for entering the scientific stage of conservation work.

Scientific Conservation Period (1980 to Present)

In the previous stage, it was necessary to carry out emergency measures to mitigate against the severe damage threatening the safety of the grottoes and their cultural relics. It was realized that such renovation and reinforcement should be performed only on endangered areas, since unevaluated measures can sometimes lead to harmful side effects and cause further damage. The conservation measures that were undertaken were appropriate to the available scientific technology at the time, and the emergency repairs helped to stabilize seriously threatened grottoes.

Certainly, long-term management and safety of the Dunhuang grottoes cannot be limited to renovation and reinforcement measures; it should focus on scientific conservation with a primary emphasis on prevention. During this phase, therefore, the conservation team formulated a long-term scientific plan, trained conservation technicians, instituted protection measures, adopted advanced technologies, expanded international cooperation, and improved management to ensure greater development of conservation work than in the previous stage. The work carried out during this period emphasized (1) an interdisciplinary approach and the application of advanced technology, (2) scientific research on mechanisms of deterioration and techniques of restoration, and (3) development from microprotection at a local level to macroconservation of the entire site. During this period, the work focused primarily on environmental monitoring and visitor management.

Environmental monitoring and research of the site

The natural environment in which the caves are located is very complicated. During this period, various scientific approaches were undertaken to understand the characteristics of the grotto sites, the natural environment

in which they are found, and the relationship between these factors. Studies were also conducted on the deterioration of and causes of damage to statues and wall paintings in the grottoes.

Approaches to environmental monitoring

The present conditions of the caves, sculptures, and murals inside the caves are complex, and their management and protection are affected by environmental factors. Several scientific approaches were taken to monitor the cave relics and their natural environment from diverse aspects, as follows:

Weather monitoring. A fully automated weather station was installed above the Mogao caves to measure temperature, humidity, ground-surface temperature, wind direction, wind speed, sunlight, and precipitation. Accurate data collected over four years reveal the basic characteristics of weather patterns and provide scientific data for studying the microenvironment and the causes of deterioration inside the caves (Li and Zhang 1993; Miura 1993).

Microenvironmental monitoring. Caves of different sizes, different depths, different levels, with and without doors, and open or restricted to visitors were selected for long- and short-term monitoring of the microenvironment inside the caves using fully or semiautomated equipment. The data obtained provided scientific evidence for the study of the preservation of murals and sculptures, causes of deterioration, the effects of visitors on the caves, and the study of the optimum environment in the caves (Zhang and Wang 1993).

Hydrogeology. Systematic analyses were carried out on the chemical components of the ground-surface water from the Daquan River and on the cliff rock of the Mogao caves. Results show that the ground-surface water has a high content of soluble salts. Dampness in the caves on the lower level was found to be brought about by the capillary movement of irrigation water that permeated into the lower levels of the caves and damaged the paintings. Studies also showed that the precipitation that infiltrates downward into the upper layer of the Mogao caves, along with the pressure exerted by the overlying rock, led to the delamination and thinning of roofs in caves at the upper level (Zhang Mingquan 1993).

Engineering Geology. Surveys were carried out to study the structure and stratigraphy of the Mogao grottoes and damage to them. Studies of the physical and mechanical properties of the cliff rock were also conducted (Zhou 1993). Tectonic and seismic analyses, and earthquake predictions in recent years, indicate that there could be an earthquake of 6.5 to 7 on the Richter scale in the Hexi Corridor area in the future. For this reason, mechanical-type concrete strain gauges were installed at observation points along major crevices in the Mogao bedrock to monitor stability. A seismic recorder was set up to record seismic activity, analyze vibration resistance of the cliff rock and reinforcement structures, and evaluate earthquake hazards in the region (Yao 1993).

Wind monitoring. Wind direction and speed, windblown sand on the plateau, and the quantity of sand transported were continuously monitored using the weather station data and monitoring devices.

Material analysis of the paintings and polychrome sculpture. Analysis was performed on the support layer, the ground layer, and the pigment layer of the wall paintings and the polychrome statues. The types, structures, and characteristics of the binding media mixed in the pigments were also scientifically analyzed (Guo 1993b; Xu 1993; Li Shi 1993).

Investigation and treatment of causes of deterioration

Deterioration to the art within the grottoes caused by different factors posed the most difficult problems. The conservation team first considered the most severe deterioration, such as discoloration of the wall paintings, obscuring of the art by windblown sand, and salt efflorescence. Experiments were conducted to prevent and remedy these processes, and the measures applied were evaluated.

Search for the causes of deterioration

Damage by windblown sand is severe, and large amounts of sand enter the grotto area. This has not only led to the annual accumulation of 3,000 m^3 of sand at the base of the cliff and on the walkways; it has also caused abrasion of the cliff and left many precarious, overhanging rocks that threaten the safety of the site. Sand and dust have also polluted and abraded the surfaces of the wall paintings and polychrome statues. In less severe cases, partial flaking of paint layers has occurred, leading to loss of luster. In severe cases, all of the paint has flaked off (Ling Yuquan 1993).

Salt efflorescence—one of the most common forms of damage to the wall paintings—can cause cracking, flaking, and even detachment of the plaster ground of the murals. Cave 53 at the lower level of the Mogao grottoes is a typical example of a cave that has suffered severe damage due to salt efflorescence (Guo 1993a). Comprehensive analyses of the geological structure of the site and the chemical components of the plaster ground layer, along with monitoring data on the microclimate, indicate that underground water seeped into the cave, raising the humidity and dissolving the soluble salts in the rock. Damage to wall paintings also occurred when water-evaporated salts crystallized between the rock and the clay plaster layer, and at the bases and tops of the murals.

Discoloration of paint pigments is very common in grottoes of various periods, especially in those painted during the Tang and Sui dynasties. To understand the current conditions of the pigments and the processes and causes of discoloration, the authors conducted two types of studies. In one, a chromometer was used in certain caves twice a year to monitor color change in pigments. In this way, it was possible to document the current condition of different colors and quantitatively monitor the process of discoloration. These data can also be used to assess the appropriateness of different conservation measures. In another study, the causes and mechanisms of discoloration of red lead, cinnabar, and hematite in red pigments were analyzed, based on pigment and chemical analyses from past studies (Li Zuixiong 1993a, 1993b).

The team also conducted preliminary studies on the causes of wall-paint blistering, which had led to detachment of the paint layer (Duan 1993).

Consolidation materials

Both large areas of flaking at the pigment layer and salt efflorescence at the plaster ground layer of the wall paintings need to be treated. Studies of suitable adhesives are also important. In the 1960s, two polymer materials—polyvinyl alcohol emulsion and polyvinyl acetate emulsion—were selected by testing and were used extensively in the restoration of many murals that had undergone flaking and efflorescence (Li Yunhe 1993a). With the limited research resources available at that time, only a few field tests were conducted. Now, thirty years later, scientific procedures have been carried out to evaluate the effectiveness of and to develop new applications for these synthetic emulsions. Efforts were also made to develop new consolidation materials and methods (Li Shi 1993).

Abatement of deterioration

Immediate care for the deterioration caused by flaking of paint layers, salt efflorescence of the plaster ground, sand abrasion of the grottoes, water erosion of the cliff rock, and detachment of the murals is necessary. In compliance with the conservation principles of ensuring the safety of cultural relics and of "restoration to the original state," work was carried out according to the following two guidelines: First, continue to use restoration materials and technologies that have proven effective over many years and have undergone many experimental evaluations. Second, formulate conservation programs for each type of deterioration on the basis of scientific monitoring and studies of the causes of deterioration in consultation with experts in sand control, structural engineering, and geology and by repeated field testing. For example, in order to treat the deterioration at the Yulin grottoes, comparisons were made with past work at the Mogao and Maijishan grottoes. Based on investigation, repeated consultations, and test results, anchoring cables were used to reinforce the cliff rock, crevices were grouted with a mixture of high-molar-ratio potassium silicate solution and coal ash, and the slope was stabilized with reinforcement techniques.

Tourism and site management

The rich cultural resources at the Dunhuang grottoes, improvement in local transportation conditions, and an increase in Chinese tourism have attracted a growing number of visitors from around the world, increasing the fame of this cultural site. People have become more and more interested in Dunhuang, which has led to a greater appreciation of the grotto sites and promotion of the efforts to conserve them. As additional caves open to the public each year, however, the appearance and environmental conditions of the grottoes have begun to change significantly. The increase in visitors has led to increases in traffic, garbage, discharge of waste water

and sewage, and residual waste from vehicles and boilers. It has also raised the temperature, humidity, and the amount of carbon dioxide inside the caves and has affected the stability of their microenvironments. Some visitors have damaged the site intentionally or carelessly, and some have even stolen relics. All of these factors are contributing to the deterioration of the site and threatening the preservation of the cultural relics.

Our responsibility, as conservation professionals, is to utilize scientific management principles, methods, and systems to ensure the protection of the cultural relics, to solve the conflict between protection and use, and to do a good job of preserving cultural heritage. For such an important site as Mogao, the guiding principle in opening the site to visitors has been to stress protection as the main objective while encouraging its active use. Management standards here ensure the safety of the cultural sites, maintain their original appearance, and permit scientific studies of them. Based on these principles, site-management work has been carried out in the following areas:

Meeting public demand. Many visitors travel long distances and look forward to seeing the art treasures at Dunhuang. The desires of these visitors must be respected. When visitors are pleased with their experience, they will help to promote the protection of the site. To explain the art and history of the caves to international visitors with different specialties, different levels of experience, and different languages, tour guides have been professionally trained and provided with a range of foreign language skills (English, Japanese, French, Russian, German, etc.). Most of them were trained in domestic foreign-language schools, and some were sent to Japan for language training. More than forty tour guides have mastered specific languages and can provide specialized explanations. Various pamphlets are provided; and special volumes of art books, pictures, slides, and souvenirs are also available.

Visitor management. To avoid damage or destruction of the cultural relics resulting from lack of knowledge about conservation on the part of visitors, the grottoes are opened by area and each cave by turn, limiting the number of caves open at any one time and restricting the number of people allowed to enter each cave per visit. The entrance charge has also been increased to reduce the number of visitors, and restriction signs (such as no smoking and no photography) have been posted, as required by national law. Visitation regulations and policies have also been updated.

Scientific preventive measures. As part of this plan, a collaboration was formed between the Dunhuang Academy and the Getty Conservation Institute. The conservation team set up automated or semi-automated monitoring stations to monitor temperature, humidity, wall temperature, and carbon dioxide levels in order to understand the effects of visitors on the microenvironment of the caves. A particle-velocity monitoring system was applied to measure vibrations in the grotto caused by tourists, motor vehicles, and airplanes at an airport located 15 km from the site. The team also established several indices of atmospheric quality in the grotto area to monitor the level of pollution. Through international

contracts, aluminum doors donated by Sir Ran Ran Shaw of Hong Kong were installed in most of the caves. In addition, the team constructed fences, protective glass screens, and fire-detection facilities. They also installed voice-, microwave-, and magnetic-activated alarm systems and posted a dog at the northern end of the site to prevent damage and theft.

Enhancing visitors' experience. Due to limited space inside the caves, the fragile murals cannot withstand a substantial increase in visitors and unlimited visitation. To ease the pressure of rising tourism rates and, at the same time, to fulfill the requirements of the visitors, a program was initiated to increase the number of scenic locations at the Mogao grottoes without changing the site's original appearance. The Dunhuang Conservation Display Center, financed by the Japanese government, is one such example.

Establishing comprehensive archives. The conservation team established archives documenting the contents and condition of each cave, its murals, polychrome statues, and architecture by means of descriptive documents, photographs, and drawings. Periodic inspection of the grottoes is conducted to document changes. Documentation by videotape recording and surveying was also carried out. Research has begun on compiling information about the murals and the condition of the sites by use of computer-information storage systems.

Setting up a rigorous site-management system. Strict control has been established for various uses of the caves, including opening the caves for visitation. Rigorous systems have been formulated for site management and job descriptions; management of cave facilities; periodic site inspections; control of site sanitation, water supply, and power; registration of cave use; checkout and check-in of cave door keys; visitation rules; and tour-guide work regulations. These systems are constantly being updated and revised in the course of practice.

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Projects of the Getty Conservation Institute and the State Bureau of Cultural Relics

The Mogao and Yungang Grottoes

Neville Agnew and Huang Kezhong

The Getty Conservation Institute's China projects, initiated formally in 1989, are a collaboration between the Getty Conservation Institute (GCI) and the State Bureau of Cultural Relics (SBCR) of the People's Republic of China, based in Beijing. These multifaceted projects involve conservation activities, research, and training at two important ancient Buddhist sites: the Mogao grottoes, a World Heritage Site in Gansu Province; and the Yungang grottoes in Shanxi Province.

The Getty Conservation Institute and the State Bureau of Cultural Relics of the People's Republic of China's Ministry of Culture first began exploring the possibility of collaboration in 1986. In May 1988, at the invitation of the SBCR, Luis Monreal, then director of the GCI; and Miguel Angel Corzo, then GCI Special Projects director, made a preliminary visit to China, at which time the Mogao and Yungang grottoes were identified as possible sites for a joint conservation project. In September of that year, a joint team was formed to examine the sites and their problems and discuss the objectives and specifics of a conservation program. The team consisted of representatives from the GCI—Monreal; Frank Preusser, then director of the Scientific Program; and Neville Agnew, then deputy director of the Scientific Program—joined by Huang Kezhong, then chief of grottoes in the SBCR, and site representatives Xie Tingfan of Yungang and Fan Jinshi, Li Zuixiong, and Li Yunhe of Mogao.

The United Nations Educational, Scientific, and Cultural Organization (Unesco), within the scope of the World Heritage Convention and as the relevant international organization, supported the initial establishment of the collaboration through H. Leo Teller, Unesco's representative in China. The result of the 1988 discussions was an agreement, signed in January 1989, to begin a three-phase conservation project, the first phase to take place over a period of eighteen months and the others to follow for one year each. The project work began formally at the end of 1990.

Project Objectives

The essential elements of the collaboration and design of the project were discussed in 1988 during visits to Mogao and Yungang, then later refined and set forth in the formal agreement. These included:

1. assessing and studying causes and mechanisms of deterioration of the sites due to climate, environment and pollution, and geological and hydrological factors;
2. jointly undertaking site interventions based on studies, particularly those that would address generic problems in China;
3. providing technical and scientific assistance and advice to the State Bureau of Cultural Relics and staff at the two sites;
4. providing conservation-related technical training to staff in a number of areas of need; and
5. disseminating information on conservation through publications and an international conference, to be held in China, on grotto conservation and management.

The Getty Conservation Institute's decision to be involved in significant interventions at Mogao and Yungang was based on evidence that much of the deterioration at the sites was so severe as to degrade the quality of the historic art and, in some places, fundamentally threaten the sites. Emphasis on scientific studies and technical assistance was therefore focused on the most pressing needs of the sites.

That decision still stands today and is fully endorsed by the SBCR and staff at the two sites. Until now, interventions of several kinds and technical training have been the thrust of the effort. With the site management training course held at Yungang in October 1992, the fourth of the five elements listed here was addressed, and the 1993 conference at Mogao fulfilled the last objective.

The collaboration has been exemplary, both at the institutional level (the SBCR was the overall authority, with the Dunhuang Academy and the Yungang Custody Committee as site partners) and the personal level. The agreement with the SBCR secured support for GCI travel and accommodations while in China. The labor, materials, skills, and staff contribution at the two sites have been no less impressive. The GCI provided specialist skills and technical and scientific advice where needed, as well as instrumentation and materials unavailable in China.

The SBCR successfully tapped a number of state and provincial organizations for support: the Institute for Desert Research of the Academia Sinica, based in Lanzhou, undertook studies for sand control at Mogao; the Datong Environmental Protection Agency participated in pollution monitoring at Yungang; the Architectural Division of the China National Institute of Cultural Property designed temple facades for several grottoes at Yungang in connection with site presentation and pollution mitigation initiatives; and the Shanxi Province Geophysical Institute provided geological and hydrological information at Yungang.

Work Completed

The following summarizes activities at the two sites until the end of 1993. (Elsewhere in these proceedings, descriptions of certain component projects of the collaboration are presented in greater detail.)

Mogao

The following activities have taken place at the Mogao grottoes:

- constructing a synthetic-fabric wind fence, approximately 3.5 km long, to control sand;
- establishing a vegetation fence, using local desert-adapted plants with drip irrigation, to provide a long-term solution to sand migration;
- installing a solar-powered, autonomous meteorological and environmental monitoring station and two cave monitoring stations to record microclimate and assess the effects of visitors on the atmosphere within the monitored caves;
- undertaking color monitoring, along with technical training, to provide information on the pigment color stability of wall paintings;
- undertaking measurement and monitoring of cracks and fissures, with technical training, to address questions of geological stability of the cliff;
- providing dust monitoring within selected caves to relate the effectiveness of the wind fences and dust filters on the doors of the grottoes;
- undertaking analysis of environmental monitoring data and providing training in computing and data reduction to help the Dunhuang Academy staff develop independence in scientific monitoring; and
- performing various preliminary tests and installations, including filters and sweeps on doors for dust control; thin-roofed cave reinforcement using lightweight, synthetic geotextiles; tests on sand and rock stabilization for the cliff slope to address erosion; consultation on grouting technology and materials to stabilize the cliff; and engineering consultancy and advice in relation to the cliff face stability.

Yungang

The following activities have taken place at Yungang:

- intensive monitoring of pollutants and particulates, initially over one month, with training in the use of equipment for additional sampling by Yungang staff over a twelve-month period;
- installing an environmental monitoring station and providing preliminary training in equipment handling, maintenance, and data reduction;
- conducting a geophysical and soil-depth study of the cliff top and Ming dynasty fort area, and introducing neutron probe and dielectric probe instrumentation for moisture monitoring in the cliff rock;

- providing engineering consultancy and advice in relation to moisture seepage and monitoring;
- developing plans for control of water infiltration and seepage into the geological strata of the cliff, using information provided in part by the provincial geophysical institute;
- conducting a preliminary design study for the pagoda facade at Cave 19 in conjunction with architects from the China National Institute of Cultural Property;
- conducting a one-year study of the pigments and binding media of the polychromy in Cave 6;
- providing a formal, two-week-long training course for site managers from other sites in China in October 1992; and
- installing two drainage test areas, each 50 × 50 m above the grottoes, using modern geosynthetic drainage materials to function with existing open-channel surface drains.

By the end of 1993, the collaboration had achieved

- solutions to some of the major problems afflicting the sites, or had demonstrated how these may be solved and what is required to do so;
- training in a number of scientific and technical areas, and in the management of sites;
- enhanced self-sufficiency in site conservation in China;
- furthering of the scientific study and understanding of the conservation of outdoor sites generally; and
- dissemination of the knowledge through publications and the 1993 conference.

The 1993 conference

The international conference on the conservation of grotto sites, Conservation of Ancient Sites on the Silk Road, held in Dunhuang 3–8 October 1993, was attended by some two hundred delegates from thirty countries worldwide. With more than sixty papers presented on art history, science, management, and conservation techniques, the conference was a signal event in bringing together East and West for the benefit of the cultural heritage of China and beyond.

Formal Evaluation of the Collaboration Project

Evaluation of the collaboration between the GCI and the SBCR was envisaged from the beginning to be essential to the project. The purpose of the evaluation was, as with all such assessments, to learn from past experience to be able to improve on possible future undertakings. The evaluation team comprised three independent evaluators chosen by the GCI and three independent evaluators from within China. Their charge was to visit the sites, interview the project staff, and assess the overall projects in terms of

design, implementation, results, and areas for improvement. Specifically, the evaluators were asked not to judge the performance of individuals or project teams but rather to assess the overall aspects of the project that were relevant to the attainment of common objectives.

Preliminary meetings were held in China and in the United States, to brief the evaluators on their objectives and to work out the logistics of the two-week trip to the sites of Mogao and Yungang, with wrap-up meetings in Beijing.

The evaluation trip occurred in July 1994. Allowing time for report writing, and translations from English into Chinese and vice versa of the independent reports of the GCI and the SBCR, the final meetings were held in Los Angeles in June 1995. These were attended by directors from the GCI and the SBCR and project leaders, as well as certain evaluators.

The results of the evaluation process were most useful to both sides in that they established a methodology for evaluation of collaborative projects of this type, examined the project design and objectives, addressed the implementation of the project, and evaluated the results achieved and their effectiveness.

The findings of the joint evaluation overall were favorable in each of the categories of evaluation, while identifying certain weaknesses of logistics, coordination, duration of campaigns, and sustainability that need to be addressed in any future collaborative undertakings.

Future Collaboration between the GCI and the SBCR

Following the evaluation and the subsequent meetings in China in late 1995, the parties concerned are in the process of discussing future needs in conservation of the cultural heritage in China. During 1996, implementation of this work will have begun, building on the solid base of collaboration and friendship established in previous years of work by the Getty Conservation Institute and the State Bureau of Cultural Relics in the People's Republic of China.

KEYNOTE ADDRESS

The Management of Ancient Chinese Cave Temples

A Site-Management Training Course at the Yungang Grottoes

Sharon Sullivan

In 1988, the author was invited by the Getty Conservation Institute to contribute to the development of an on-site training course in rock art site management. The course demonstrated that the combination of a good planning framework and simple, cost-effective management techniques had much to contribute to the preservation of sites.

The planning framework for the course was based on the Burra Charter (an Australian adaptation of the Venice Charter), with some change in emphasis to suit the particular needs of the participants. The Burra Charter established a methodology and sequence for the management and conservation of cultural heritage sites. Figure 1 illustrates this framework, consisting of the planning process, its sequence, and the steps carried out by the participants in the course of the training period.

In 1991, two representatives of the State Bureau of Cultural Relics of the People's Republic of China, Huang Kezhong and Sheng Wei Wei, participated in one of the training courses. By that time, the GCI had been involved for several years in conservation work at the ancient cave temples, or grottoes, of the Silk Road. Following the attendance of the Chinese participants, it was decided that a course could be adapted to suit the need for grotto conservation and site management in China. Therefore, a training course was set up by the GCI to be held in conjunction with the Yungang Grottoes Historic Relics Research Institute near Datong. A capital of China during the Northern Wei dynasty, Datong is located northwest of Beijing in Shanxi Province, near the border with Inner Mongolia, and is the site of cave temples dating from the fifth century C.E.

In April 1992, a preparatory trip was undertaken to visit a range of cultural sites in China. This established the framework for the course, which was held in October of that year and attracted site managers, specialists, and administrators from various areas in China. Participants and staff were housed at the Yungang grottoes, which was also used as a major case study.

The course consisted of lectures, illustrated by examples from different parts of the world; group discussions and exercises; and the preparation and presentation by the participants of the various aspects of a

Figure 1
The step-by-step process followed during the site-management training course at Dunhuang (after Kerr 1985).

Planning Process for the Conservation of Archaeological Sites

Step 1

Location and documentation of the site or sites

- survey
- inventory
- historical and archaeological record
- graphic archive

Step 2	Step 3	Step 4
Significance assessment • establish values • formal statement of significance **What value does this site have?**	**Condition assessment** • document physical condition **What is the condition of this site?**	**Management assessment** • establish constraints and opportunities **What are the constraints and opportunities that will influence the management of this site?**

Step 5

Defining the management policy

- statement of purpose and set of principles or policies based on assessments

Why is this site going to be managed?

Step 6

Choosing the management strategies

- specific practices

How will the management objective be put into practice?

Maintenance strategies	Conservation strategies	Visitor strategies	Other strategies

Step 7

Monitoring, varying

management plan, culminating in a completed plan by the end of the course. Field exercises included the preparation of documentary drawings, comparison of 1930s photographs of the site with the site today, and assessment of the site's significance and its management environment. The latter was evaluated using a SWOT technique—an analysis of strengths and weaknesses, opportunities, and threats—followed by the development of

management objectives and strategies. Visitor surveys and visitor observations, designed and run by the participants, as well as condition surveys, provided valuable data to feed into management planning.

The nexus between management and conservation

In the field of conservation, the terms *management* and *conservation* are sometimes used interchangeably to mean all or some of those actions that are taken to ensure the long-term conservation and appropriate use of a cultural site. This may include such steps as documentation policy, significance assessment, physical research and intervention, and visitor management.

In this article, the term *management planning* is used to mean the overarching framework by which one establishes a series of appropriate steps to preserve a site, including physical conservation. The term *physical conservation* is used to mean those interventions carried out on the fabric of the site or its environment aimed at lengthening the life of that fabric. The term *preservation* is used to refer to the desired outcome of the management—the best, most efficient, and most appropriate way of achieving the long-term existence of the site and its cultural value.

The Step-by-Step Approach to Management Planning

Figure 1 shows the steps in a management planning exercise, as carried out in sequence by the participants of the conservation management training course. These are, in brief:

1. Location, identification, and documentation of the archaeological site or sites
2. Assessment of the value or significance of the site to the community or particular sections of the community, bearing in mind that "community" can apply to groups from the international to the local level
3. Assessment of the physical condition of the site
4. Weighing the values of the site with a range of management opportunities and constraints, including its physical condition, available management powers, resources, and experts
5. Arriving at a management policy or management objectives for the future of the site
6. Implementation of appropriate management strategies (including ongoing maintenance) in accordance with the management policy
7. Supervising and checking the proposed strategies and adjusting and altering them as required

In running the course, a number of concepts needed to be conveyed: First, the series of steps is a process with its own logical order; and getting the process right, complete, and in sequence is the real secret of management success. Second, the framework is empty until it is filled by

the managers themselves. That is, there is no magic recipe for management or preservation; rather, it must arise out of the adaptation of the process to local conditions and traditions, including the social, economic, political, and physical environment.

The grotto sites in China are beautiful, ancient, and of great cultural value. They also represent a great variation of fabric condition and management issues. They are often very large. Some of the elaborately carved and/or painted surfaces are still in good condition and are covered by wooden temple facades or other more modern structures. Some are completely exposed; and wind, sand, and water damage have accrued over a long period. Almost two millennia of conservation, restoration, and adaptation make a complex and technically daunting mix of interpretation and conservation problems. Pollution is also a major problem. The sites are often well staffed, but an increasing flow of visitors is causing a range of problems and is forcing the authorities to consider increasingly interventionist site-management techniques. In some areas, traditional religious use is still evident and is growing again. This brings its own set of dilemmas and management issues, especially delicate in the modern secular state.

The value of these sites, and the apparent gravity of many of their problems, seems to call for instant action—a drainage treatment here, a visitor center there, a newly invented scientific technique somewhere else. Yet, unless conservation managers analyze the whole site, and the whole problem, and systematically plan management in a logical way, they can do more harm than good.

In China, as in Australia and the United States, the managers (the participants, in this case) showed an initial tendency to leap to solutions rather than to diagnose and plan—to treat obvious symptoms without first properly analyzing the site and the management situation. There was a feeling that the value of the sites and their problems were well known, and that what was needed from the conservation professional was the latest, most scientific, and preferably the most high-tech solutions. As the training course showed, the initial assumptions of the teaching staff, and those of the participants, were just that; and also that simple, time-honored methods are often as useful, and more relevant, than imported solutions.

The secret of successful management is to develop a plan that suits the long-term needs and abilities of local management and that responds to the multiple values a site may have. Perhaps the best way of illustrating this in the case of the grotto sites is to run through some of the elements of the process, as we worked through it at Datong, and to explain some of the conclusions and outcomes that the participants developed and presented as their application of the management-planning process to local conditions.

Documentation and condition assessment

The first step taken was the documentation of the history of the site. This, along with step 3 (condition assessment), is discussed by Stephen Rickerby

elsewhere in this volume. Suffice it to say here that participants were able to use the previous documentation of the site to assess its condition and to deduce sequences of events as a prerequisite for analyzing the causes of physical problems. The documentation phase was also essential in identifying and analyzing all the elements of the site's value. This initial work assisted everyone in correcting some previous assumptions about the site and its significance.

Significance assessment

Following the documentation phase, the next step was to assess the value of the site; that is, to systematically list and analyze all the elements that contributed to the site having cultural value to the Chinese people and to humanity in general. Initially, participants seemed skeptical of the need to assess significance, since the value of these sites appeared to be abundantly clear, but analysis of this range of issues demonstrated (as always) that the concept of significance assessment is a very powerful tool for analyzing a site's management needs. The site's historic, scientific, aesthetic, social, and other values were considered.

Where does significance reside?

There was much discussion about the significance of different elements of the site, especially about the question of previous restoration and reconstruction. Was this part of the site's significance, or should it be removed? Was the Ming dynasty fort on top of the older site important? Where did the question of religious use today fit in? Was this a legitimate value for the site? How would it effect its management? Did participants agree with a 1970s article, which—after an excellent description of the site and survey of all these elements—stated that the outstanding significance of the site was that "each work here steeped in the blood and sweat of the artisans serves as evidence of the crimes perpetrated by the ruling clans of old" (Yungang Grottoes Custody Committee 1977:15)?

A fascinating and much-argued issue focused on previous "traditional" conservation and restoration methods. Over two millennia, devoted monks, patrons, and, in some cases, rulers had sporadically conserved, restored, and adapted the sites. Re-carving, supporting stone carvings with iron spikes, replacing decayed stonework with painted clay moldings, and rebuilding shelters has ensured that the sites have reached the late twentieth century in a relatively intact state and has also provided a myriad of technical problems and interpretive puzzles. Is this previous work significant? Can it even be called conservation? How will sites be managed now that their ongoing traditional care has ceased with the twentieth-century disappearance of their traditional guardians and has been replaced with an equally devoted but very different set of managers with a different set of aims?

The analysis of such issues led to lively discussion and disagreement between and among the work groups, and also amply demonstrated the necessity of assessing significance prior to carrying out management

strategies, including physical conservation. For instance, if it were decided that the major significance of the site was to teach about the crimes of the ancient clans, the presentation of the site to the public would be very different than if it were decided that its artistic and religious values were of prime importance. Similarly, the participants decided that change, adaptation, and conservation of the site over sixteen hundred years was as significant as the original, or oldest, paintings and carvings. Hence, the management policy decided on was to conserve all elements and periods of the site's fabric and not, for example, to interfere with one in order to find an earlier one.

Arriving at consensus

Despite their different views, the participants were able to produce a succinct statement of significance summarizing the values of the site. Some key elements proposed in the process of significance assessment included the following:

- A range of expertise and thorough investigation of differing views are needed to enable full investigation of all the elements of significance.
- The significance of a site is usually multifaceted, and any management strategy must consider all the elements and resolve potential conflicts between major ones.
- Significance of a site can change dramatically over time, and from culture to culture, and will require periodic reassessment and reanalysis.
- The role of site managers in assessing values is very important; they must ensure that the correct expertise is brought to bear and must, because of their special and holistic knowledge, take a leading role in the assessment.

One issue that emerged during the course was the immense amount of documentary and other evidence available about Chinese grotto sites; this is in contrast to most Western sites of the same period, and certainly to Australian Aboriginal sites. This "embarrassment of riches" needed editing to ensure that key points could be distilled from it.

Weighing significance and constraints

Following the assessment of significance, it was necessary to assess both the physical condition of the site (step 3) and the management condition or environment (step 4). Many technically brilliant and meticulously researched plans for physical conservation or ongoing management are never implemented. One important reason is that they are totally inappropriate for the management environment in which they are supposed to operate. Expensive machinery that cannot be maintained, or complex monitoring procedures that rely on a consistently high budget and a training commitment that is not feasible, are useless and do more harm than good.

The only plan that will work is one that suits local circumstances and, equally important, one that has been devised—or at least enthusiastically accepted—by local management. That was why the course was designed around the participants themselves preparing and presenting "a plan"—to ensure that it respected local conditions and that they "owned" it. A crucial step in this process was for the participants, with generous and frank information from local staff, to carry out a SWOT analysis of the site and its management. Thus, the participants looked in some detail at budgets and staffing, visitor numbers and physical problems, local political support and government policy in order to establish, in a realistic way, the management situation and plans that would be reasonable and useful to apply in this situation.

Arising out of this, the participants were able to look at significant threats (e.g., local levels of pollution) and opportunities (e.g., the possibility of a changed pricing policy for visitors). The participants engaged enthusiastically in this exercise and made great use of local staff, who, in turn, were challenged to consider questions and ideas they had not previously examined in such detail. In this exercise, and throughout the course, the participants acted as management consultants to the local staff, carrying out an assessment of present management and bringing a new perspective and a fresh outside view to a familiar situation and familiar problems—a very helpful step in the creation of a management plan.

Formulating a management policy

With all this information—on significance, on condition, and on the management environment—participants and teachers turned their attention to formulating a management policy for the site. A management policy determines how the cultural significance of the site, identified by the statement of significance, may best be conserved in the short and long terms, taking into account the particular constraints, problems, opportunities, and circumstances that relate to the site. It should cover, in general terms, policy for use, interpretation, management structure, physical intervention, investigation, future activities, mitigation, and salvage (if appropriate), and provisions for monitoring and review. The policy should clearly state the options available and the way in which the implementation of the management policy will "change the place, including its setting, affect its significance, affect the locality and its amenity, affect the client owner and user, affect others involved" (Australia ICOMOS 1988:10).

While it is easy to describe the requirements for a management or conservation policy, achieving a successful and workable policy that will effectively maximize the conservation opportunities for a site is often a complex and multifaceted task, requiring technical expertise, sound judgment, practical common sense, lateral thinking, and adaptability. These are the skills the site manager needs. The policy cannot be achieved by a recipe, or simply by hiring an appropriate expert. It requires the attention and management skill of the manager and the commitment of the organization or authority responsible for the management of the site.

The participants were specifically requested to design a policy that

- articulated the implications of the statement of significance;
- was acceptable to the owner/authority who controlled the site;
- paid due attention to the needs and desires of the community, especially to those with a special interest in the site;
- was financially feasible and economically viable;
- was technically feasible and appropriate;
- provided a long-term management framework; and
- was sufficiently flexible to allow review, improvement, or alteration.

In the course of this exercise, a number of issues crucial to the future of the site emerged. Participants and staff found themselves considering a range of issues and making decisions about questions such as:

- whether the protection of the carvings by the erection of an intrusive structure is more in keeping with the stated significance and management context than leaving them exposed, or whether it is more appropriate to protect them less completely and keep the setting and aesthetic feeling of the site more intact;
- whether to allow access to a particular part of the site that is very significant to visitors—perhaps to people practicing religious rites—or to prevent this type of activity because it may damage the site;
- how best to interpret the site—with signs, brochures, a visitor center, guided tours, or a combination of these;
- whether the natural vegetation should be left, removed, or restored, depending on its importance and its effect on other significant elements of the site;
- whether research will be allowed on the site, and if so by whom, and in what circumstances; and
- what the best makeup of the staff might be, including the roles and priority of guides, guards, scientists, and managers.

Implementation strategies

The next stage of the training course (and the plan) was step 6, the management strategies—those actual, on-site steps through which the management policy would be put into action. Once again it was important to understand the holistic nature of the exercise. Provision for a range of strategies was necessary to ensure the ongoing preservation of the site.

A range of strategies was explored and suggested by participants. These included elements such as

- ongoing documentation, assessment and research;
- maintenance and updating of records;

- physical protection of site boundaries;
- controlling impinging development and local atmospheric and other environmental problems;
- regeneration and creation of a wider buffer zone;
- regulation, control, and direction of research;
- salvage procedures, and methods for ensuring that work on the site did not affect the significant site fabric;
- curating movable artifacts; and
- arranging for ongoing consultation with and involvement of particular key people and groups.

The course placed special emphasis on maintenance, conservation, and visitor-management strategies as being the most fundamental and useful. The physical conservation strategies suggested were the subject of intense debate. A key question here (as elsewhere) was the extent of intervention required or desirable, the necessity for research to establish the nature of the problem, and the potential results of intervention.

The development of maintenance and visitor-management strategies perhaps most dramatically demonstrated the effect that site managers could have on site preservation through relatively simple practices. Simple maintenance measures—such as keeping doors and windows of protective structures maintained and shut, keeping dust levels down, removing vegetation where appropriate, and closely supervising outside workers on-site—all emerged as equally, if not more, important in terms of preservation as some of the more elaborate and costly proposals for physical conservation.

Figure 2
The observation strategy used by course participants.

Yungang Grottoes Visitor Observation

Observers

In groups of three:

- one person recording information
- one person giving information
- one person walking around observing

At Caves 5 and 6, during a specific time period.

Observations

- Are people smoking near or inside the building?
  If so, how many?
- Are people touching the structure?
  If so, how many?
  In what places?
- How long does the visitor stay inside the structure (and cave)?
- Do people go into both Caves 5 and 6, or do they tend to go into just one?
- Note the length of time of your observation.
- Keep a count of the number of visitors you observe.

Figure 3
The script employed for surveying visitors to the grottoes.

Yungang Grottoes Visitor Survey

Hello! (Wear your name tag and introduce yourself.)
We are doing a survey of our visitors. Could we ask you a few questions? This will take only a few minutes, and your answers will help us in managing this site.

1. Where do you come from?
2. What kind of work do you do?
3. We are interested to know why you are visiting Yungang:
   - family holiday
   - business/conference
   - group visit/work unit
   - other
4. How did you first learn about the Yungang grottoes?
   - school
   - travel agency
   - tourist guidebook/map
   - friend
   - local knowledge
   - other
5. Have you visited other grotto sites? If so, which ones?
6. Is this your first visit here? If no, how many times have you been here?
7. Which part of the site interested you most?

   Which part was least interesting? Why?

   Which caves do you think are most important?
8. Did you know that there is a Ming-dynasty fortress above the grottoes?
9. Are you satisfied with the facilities for the visitors (e.g., restrooms, souvenirs, etc.)?
10. Would you like to have learned more from your visit? What?
11. In your opinion, was the cost of your ticket appropriate?

    Would you be willing to pay more for a ticket?
12. In your opinion, is the site well cared for?

    Do you have any suggestions for improvement?
13. May I ask you what age group you fit into?

    15–25
    26–40
    41–55
    55+

Thank you very much for your time. The information you have given us will be very valuable to our work.

The visitor observation and survey exercise

The value of simple techniques was made even more dramatically clear through the work the participants did in the area of visitor management. On the first Sunday of the course (Sunday being the busiest day at the site for visitors), they designed and carried out a visitor observation and survey exercise. A group of participants observed visitors at certain grottoes and made notes about their behavior in accordance with instructions previously formulated with the lecturers (Fig. 2).

At the same time, other participants conducted their first-ever visitor survey (Fig. 3), interviewing some ninety visitors on-site, with the help of interpreters, as needed. There was some concern about whether the visitors would receive such questioning with equanimity. As it turned out,

however, both participants and visitors enjoyed the experience greatly. According to student reports, the visitors appeared to appreciate the fact that the site managers were interested in their opinions and in improving management. The visitor studies were based on the work of Fay Gale at Australian Aboriginal art sites for the Australian Heritage Commission (Gale and Jacobs 1987). The results of the work are too numerous to detail here; however, a number of key points emerged that are very relevant to principles of management generally, as follows:

When considering the general problems of site management, participants were overwhelmed by the immense problems of gradual and relentless physical deterioration, due to natural causes, which the managers of the sites have been battling from the beginning. These problems are grave and inevitable; and they deserve attention. However, as Stephen Rickerby points out elsewhere in this volume, the deterioration is often much more gradual than it would at first appear.

In contrast, the effect of poorly behaved visitors can be catastrophic in a short time. The participants found this from their unobtrusive observations of visitors on-site. In particular, a group of young boys spent the afternoon roaming through the site, and when they thought they were unobserved, climbed up on the large painted statues, sat in their laps, and scratched them with their feet. This seemed to be a regular occupation, as the boys were searching for money left as offerings. The clearly observable fact was that the boys, in one afternoon, were able to do more damage to these figures than ten or perhaps a hundred years of natural weathering.

This and other visitor-management problems were not the result of neglect or negligence. They simply required systematic observation on the part of managers and the consequent application of suitable management measures. The participants readily suggested solutions that were relatively simple, inexpensive, and low-tech, yet impressive in terms of the long-term preservation of the site. Similarly, observation of visitor-flow patterns resulted in a greatly enhanced design for a system of visitor management.

In the same way, by means of the visitor survey, the participants gained extensive information about the origins, expectations, and views of visitors, who were not at all reluctant about voicing their opinions and making suggestions for improvements. The survey assisted immensely in designing a visitor and interpretative strategy. Had the participants attempted to design these without such a survey, they would certainly have made some significant mistakes. For example, visitors showed a strong desire for on-site information and interpretation, for more guided tours, and for better facilities. Equally important, they stated that they would be willing to pay more for these services.

The management plan

The course concluded with the presentation of a management plan by each group to a jury and to fellow participants, who did not hesitate to

rigorously question the logic of proposed solutions and lobby for their own proposals. All the plans had key similar elements: all proposed practical, and sometimes very imaginative, solutions to management problems; and all demonstrated that the expertise necessary for the successful ongoing management of the sites was locally available among the participants themselves. Perhaps most important, all groups used the planning framework in a logical way, and they clearly demonstrated their understanding of the process and its benefits.

Conclusions

A number of conclusions with general application can be drawn from the experience of participants and teachers in this management experiment. First, the simplicity and logic of the process itself was self-evident by the end of the course. Its real contribution—and the reason it was so easily adaptable—was that it pulled together, strengthened, and added to present local planning principles and practices. It is a fundamental principle of site management that such a process be used as a discipline.

Second, its use and adaptation by the participants to local outlooks, philosophy, and management environment was crucial. The lecturers and the plan outline provided only the framework for the participants' input. They had the relevant background, information, and expertise to actually produce the finished plans. To be successful, a management plan cannot depend on complex Western technology or high-tech solutions. It must be designed by the key decision makers at a number of levels; it must be acceptable to the local community; and it must be able to be implemented in the local political, social, and technical environment.

It follows, therefore, that a "perfect" plan, which instantly identifies and solves all the major problems of the site, is unrealistic and unobtainable. Westerners often take, or are given, the role of "fixers," usually by way of complex new methods and the input of major resources. Yet management planning, to be successful, needs to move in small, discernible steps from the known to the new, from the present situation to incremental change for the better. Management-strategy development is iterative and gradual. Because of this, physical conservation measures need to be an integral part of management planning and will not succeed if they get too far ahead of this process in terms of available technical or logistical support and follow-through.

Effective management planning can identify basic, low-cost measures for conservation. The establishment of a viable, ongoing management framework and a management plan to achieve certain specified ends are, in fact, essential prerequisites to any significant decisions about physical conservation that involve intervention in the fabric.

In the process of developing the plans during the course, it was also necessary to understand and come to terms with philosophical differences between the Eastern and Western approaches to material conservation. Perhaps the most animated discussions in the entire course focused on the question of an appropriate strategy for physical conservation, one that flowed from the statement of significance and

the management climate. The discussion took place toward the end of the course, when the elements of the plan were falling into place and when participants and staff had established a degree of empathy difficult to achieve quickly, especially through language interpretation. Discussion came at last to focus on the significance of the site and on the nature of the Chinese "sense of place" and its implications for management. Many participants argued strongly for the validity of a more interventionist approach to conservation than is usual in current Western methodology, including a greater emphasis on reconstruction (Wei and Aass 1989:3–8). The discussion and its outcomes demonstrated the robustness of the planning framework and the necessity for local managers to "fill out" any such framework in accordance with the cultural traditions of their own society.

Teaching the course was a great experience. The enthusiasm and intelligence of the participants, the beauty and complexity of the site, and the challenging and fascinating differences between the Western and Eastern cultures, which the course forced us all to confront, made the experience most exciting and rewarding. It gave the participants great insights into the question that brings us all together: "What, then, shall we do?"

Acknowledgments

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Management of Tourism at Buddhist Sites

Robertson E. Collins

For centuries the Silk Road was a vibrant trade route. It was also an important travel route for people and ideas. In general, exotic goods moved from the East to the West; merchants, missionaries, ideas, and money moved from the West to the East. Buddhism was the first religion to travel west, and then east, along the Silk Road.

Around 200 B.C.E., Buddhism expanded westward from northeastern India to Taxila in what is now northern Pakistan. A century earlier, Alexander had rested in this region, then turned away from India and back to the Mediterranean. Later, around 200 C.E., this same area became the State of Gandhara under the rule of King Kanishaka, a patron of the arts. Taxila-Gandhara had enjoyed long trade and travel contacts with Greece and exposure to Mediterranean art. Here, with the support of King Kanishaka, the first sculptural representations of Buddha and the beginnings of elaborate shrine architecture began to appear.

It was from Gandhara that Buddhist religion and art traveled east along the trade routes and up over the mountains along the Silk Road into China and beyond. As Gandharan art and architecture traveled along this difficult and increasingly profitable route, it began to change. It started to reflect the value and variety of trade goods, the changing dynamics of the transplanted merchants and the local people, their systems of governance, and the great esteem in which they held this new religion.

The Silk Road has not been an active trade route for many centuries now, but today the mystique of this vast region attracts tourism, and the number of visitors is increasing daily. What began two decades ago with jeeps carrying television crews across the wasteland has now become a popular international activity. For much of its route through China, the road is now paved, though often camel tracks parallel the right-of-way. Clusters of gas stations, repair shops, motels, and cafes are appearing at once-remote trail intersections. Former camel stops and trading centers have become cities of more than a million residents.

Where it still exists, the legendary Silk Road with its unmarked track has itself become an archive—a linear museum with a limited

visitation. Traces of the Great Wall, crumbling watch towers, and abandoned settlements are reminders of the stamina and defeats of the early merchants and their caravans.

Today, Buddhism, where it survives along this ancient road in shrines or in cliff caves, attracts official caretakers rather than fervent, dedicated monks and wealthy devotees. The art of the Buddhist record is remarkable, and the sites have dramatic appeal; profitable tourism has a clear potential. The danger is that tourism pressures may overburden heritage resources. Money is needed for protection of the sites, for the interpretation of the sites to visitors, for planning a balanced tourism infrastructure.

Conservation at Buddhist sites along the Silk Road ranges from total neglect at some sites to futile battles against time, the elements, and inadequate budgets and to professional, scientific stewardship at others. At this moment in time, the energy within China as it races into the next century bodes both danger and opportunity for tourism and conservation. The scholars and curators of Buddhist sites have an enormous task before them. Tourism should be a helpful adjunct to conservation needs; but, unfortunately, tourism management is not yet sufficiently financed nor sophisticated enough to be able to enact the protective visitor controls that need to be imposed. A 1996 report by the Madrid-based World Tourism Organization indicates that China's tourism increased by 10.9% in 1995 to rank in the top five destinations in the world; and data from China indicate that the country received 46.387 million overseas tourists in that year alone (CITS 1996). Until there is some dramatic change in conservation budgets and tourism planning, the Buddhist sites along the Silk Road in China must be considered endangered.

Today, Buddhism is the daily religion of a quarter of the earth's population, and many Buddhist sites in Asia continue to be active religious pilgrimage destinations. Many long-abandoned sites have been designated by Unesco as World Heritage Sites and are also celebrated attractions for the tourism industry. Most of the recent growth at the great Asian Buddhist sites has been gradual and generally well managed. As with all World Heritage Sites and tourist attractions, however, the number of future visitors is expected to increase dramatically; at many sites the maximum capacity has already been reached. Visitor levels have risen far beyond the expectations of the original builders, frequently beyond the budgets of the conservation institutions that maintain them. Various forms of access control are being considered. For example:

- The tourism plans for the Angkor Wat temple complex in Cambodia are developing faster than its conservation plans. Similarly, Borobodur, Indonesia, experiences as many as three hundred thousand visitors per month. In both cases, these are mostly domestic tourists, and officials are being forced to consider some sort of reservation system.
- At Sigiriya in Sri Lanka, tens of thousands of people assemble each month on the evening of the full moon. The impact of

this domestic visitation is dramatic, overloading roads, utilities, and services.
- The Kandy Esala Perahera festival in August attracts thousands of people on its final day. This used to be an event for Sri Lankans only, but the once-simple religious procession of the Tooth sect has been expanded into a major event complete with bands, dancers, elephants, festival foods, and grandstands. Tickets are issued for reserved seats, and the event is advertised in Europe and America as an international attraction.
- At Lumbini, Nepal, birthplace of the Buddha, the number of tourists is rising. Rather than focusing on conservation needs, developers are building a super-scale park on and around the simple shrine, the bodhi tree, and the Ashok pillar. Visitors are being wooed with new hotels, conference and library facilities, wide roads, and a reflecting pool nearly a mile long.

Tourism is expanding all over the world, and all World Heritage Sites must anticipate increased visitation. A concurrent force is at work that poses serious problems: staggering population growth. Although the numbers of visitors to monuments and museums are already near capacity levels, cultural conservation faces increasing growth pressures in the near future.

In 1950, when the era of mass travel began, the population of the world was 2.5 billion. In 1993, forty-three years later, world population was 5.5 billion. In the year 2026, it is expected to rise to 8.5 billion. Most of this growth will occur in South America, Africa, and Asia. It is impossible to think of the future of either tourism or conservation without absorbing the implications of these statistics.

The question is how to meet that challenge. If conservation and tourism are to succeed, they must develop a planned partnership. There is a need for a comprehensive management plan for each significant site to ensure that the best levels of protection are in place that still allow visitors to have meaningful visiting experiences. This comprehensive plan must first include a plan for conservation. Only after the conservation plan is in place should a tourism plan be undertaken.

The tourism plan should be prepared by tourism professionals rather than by site scholars. Conservation specialists should address the safety and protection of the site and then turn to fellow professionals who understand the intricacies of tourism and visitor management.

Everyone is affected by tourism and has an opinion about it. In recent years, the environmental movement has prompted talk about new kinds of tourism: eco-tourism, sustainable tourism, responsible tourism, and endemic tourism are just a few of the terms used. Also in recent years, *cultural tourism* has become a popular term, now so broadly used that it no longer has a singular definition. Still, everyone seems to like the idea, and no one seems disturbed that there is no broad agreement on what cultural tourism really means. Only a few people who use the term realize that it specifically refers to visitation at monuments and sites.

Another challenge to the management of these great sites is the fact that although governments have funded most conservation programs until now, major cuts have had to be made in the budgets of conservation institutions. Yet, there is a window of opportunity: most governments in their search for money now see tourism as a source of revenue. Because great cultural assets can attract income, conservation budgets can and must, in turn, be increased.

In 1992, the Pacific Asia Travel Association (PATA) commissioned the U.S. Committee of the International Council on Monuments and Sites (US/ICOMOS) to conduct a study that it hopes will increase the level of funding for conservation work in Asia. This study is expected to justify the efforts of travel-industry leaders in their appeals to government organizations for increased conservation budgets.

In the future, conservators will have willing partners if they approach the tourism industry as a constructive collaborator in managing growth and change. In the Caribbean, for example, US/ICOMOS has conducted an awards program with the American Express Foundation, a partnership that has worked to everyone's benefit. Similar industry partnerships need to be nourished.

The Buddhist sites along the Silk Road cannot support mass tourism or local recreational visits. These are important, fragile sites; their conservation will require collaboration among historians, scholars, artists, conservation scientists. Ancient technologies and materials will need to be studied from various perspectives and conservation measures sensitively applied.

In addition to the appeal of the sites, the conservation process will itself become a tourist attraction for many years to come, attracting special "niche" tourists likely to appreciate these conservation activities. Planned properly, this type of tourism may be able to generate greater financial stability for conservation efforts at these sites. This is the paradoxical truth for conservators: tourists are needed to provide funds to protect sites from tourism.

Further, there are now alternatives to mass tourism. The numbers of people traveling are so high, it is possible to select the special segments that will best serve each site. Two recent books on managing tourism at World Heritage Sites are of particular interest (see references). One published for the ICOMOS General Assembly in Sri Lanka was written by the US/ICOMOS Committee on Cultural Tourism (1994). The other, produced as a result of a Pacific Asia Travel Association conference held in Kathmandu, contains an approved a set of guidelines for tourism management at heritage sites (PATA 1993). The Kathmandu Declaration, as it is called, emphasizes that the community residents around a site are essential to its proper presentation. These guidelines also look at good tourism as an opportunity to support professional conservation practices.

The basic rule of the tourism industry is, What is good for the residents will be good for the visitors. Domestic pilgrims will be the largest segment of visitors to most Buddhist sites, and their needs must be given priority in planning. The international segments will follow easily.

Conservation planning must come first. But sound tourism planning, within conservation limits, can also extend the historical intent of the original builders, manage visitors to ensure protection of the sites, and give pilgrims and other visitors a worthwhile and dignified visiting experience. The challenge is to find a balance between public access and professional conservation. Success will be achieved by wise application of the skills of conservation and tourism professionals alike and by a shared commitment to excellence.

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The Dambulla Rock Temple Complex, Sri Lanka

Ten Years of Management, Research, and Conservation

Senake Bandaranayake

The UNESCO World Heritage Site at Dambulla, Sri Lanka, is a monastery and temple complex that has been in continuous use since its founding in the second or third century B.C.E. Though small in comparison with Dunhuang or Ajanta, it is still one of the largest painted rock temple complexes in the South and Southeast Asian regions and one of the most important centers of Buddhist pilgrimage in Sri Lanka. Set in a rich, multiperiod archaeological landscape, Dambulla is also an extremely complex archaeological and historical site, a palimpsest reflecting successive periods of human occupation, with a history that extends from prehistoric to modern times.

The Site

Geologically, the site consists of two great rock outcrops, or inselbergs, roughly dome shaped, surrounded by boulder-strewn hill slopes, not unlike the more famous site of Sigiriya just 16 km away. The topography, natural resources, and extraordinary beauty of the site, with its massive rocks interspersed with deeply forested tracts, have made Dambulla an important focus of human activity throughout various historical periods. A map of the area today is shown in Figure 1.

Along the western slopes of the Dambulla rock are a series of large boulders, terraces, and caves that formed the habitat of prehistoric humans. Excavations have yielded remains of prehistoric stone implements, displaced from the rock shelters when they were cleaned out in early historic times. These remains indicate a process of successive waves of human activity at the site, created when one historical period overtakes another, leaving some signs or remains of its predecessors behind.

From Prehistory to History

Prehistoric peoples were succeeded by the first settlers and farmers in the first millennium B.C.E. Dambulla is surrounded by a number of megalithic cemeteries and early historic settlements, the best known of which is Ibbankatuva, which are closely linked with the Dambulla complex. It seems likely that these hinterland farming settlements, such as

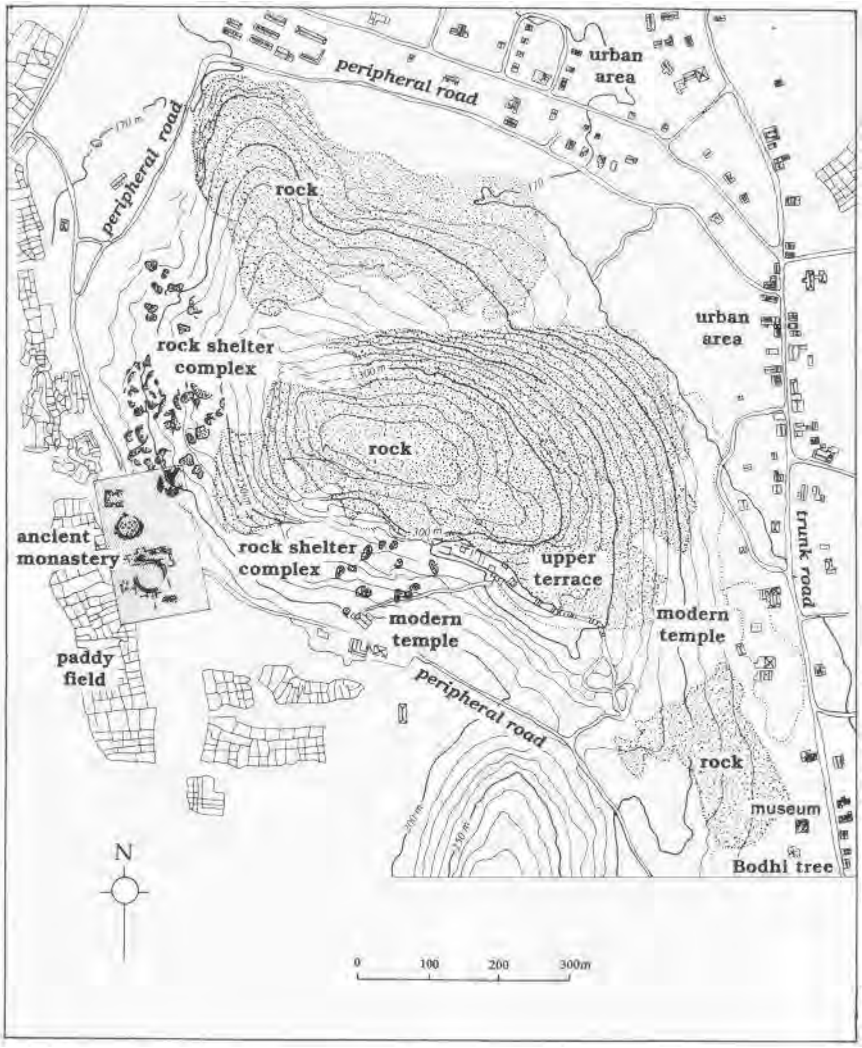

Figure 1
Map of Dambulla showing the rock shelter complexes, the ancient monastery, and the modern town and road system.

Ibbankatuva, formed the social and economic base that sustained the early Buddhist monastery at Dambulla (Bandaranayake 1988).

Some time during the third century B.C.E., the western and southern rock face and the surrounding boulder area became the location of one of the largest early Buddhist monastic settlements on the island. The area from the upper terrace downward contains eighty rock shelter residences.

The uppermost group of rock shelters on the southern face of the Dambulla rock continued into the subsequent historical period as the ritual and artistic center of the Dambulla complex (Figs. 2, 3). This upper terrace seems to have been in continuous occupation for more than twenty-two centuries, up to the present day.

The central shrines of the Dambulla complex were formed out of a deep cavern—part natural, part excavated—more than halfway up the western slope of the rock. Screen walls and partitions have created a number of separate chambers, or *viharas,* five of which are in use today (Fig. 4).

During the middle historic period (ca. fifth to thirteenth century C.E.), Dambulla continued to develop as a major religious center. An

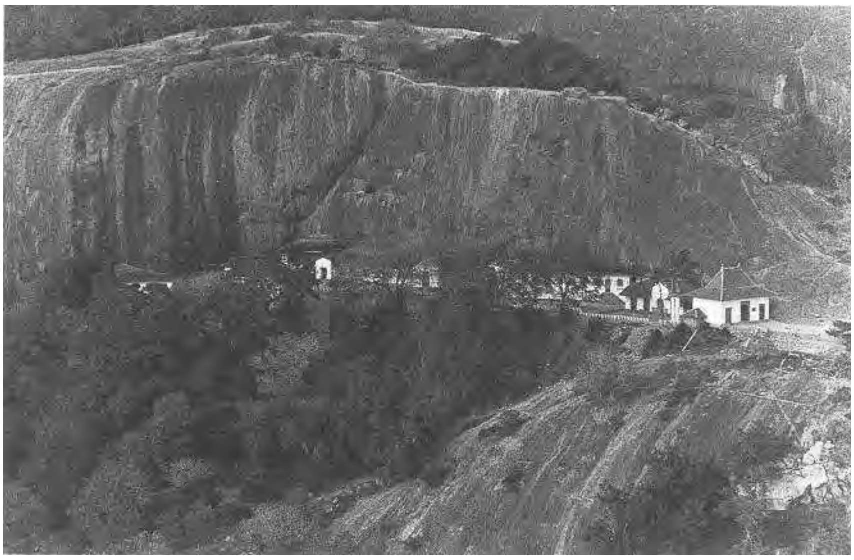

Figure 2
The Dambulla rock temple complex, upper terrace.

Figure 3
The upper terrace, shown with visitors.

important development was the expansion of the temple into an elaborate, freestanding architectural complex at the foot of the rock in the southwestern sector. The upper terrace temples were refurbished at the end of the twelfth century and again in the reign of King Senarat (1604–35), before their complete restoration and repainting during the eighteenth-century Buddhist revival under King Kirti Sri Rajasinha (1747–82) (Bandaranayake 1986). This great eighteenth-century painting cycle remains substantially preserved today, with some additions made in the early nineteenth, mid–nineteenth, and early twentieth centuries.

Sri Lankan Rock Temples

Dambulla as it exists today is one of the best preserved of more than one hundred painted and sculpted rock temples in Sri Lanka (Figs. 5–8). These temples have their origins in a series of early Buddhist rock shelter monasteries. Dating from the period between the third and the first century B.C.E., and distributed throughout the length and breadth of the country, these monasteries are of a specific Sri Lankan type. Located among

Figure 4
The Dambulla rock temple complex, site plan of the viharas on the upper terrace.

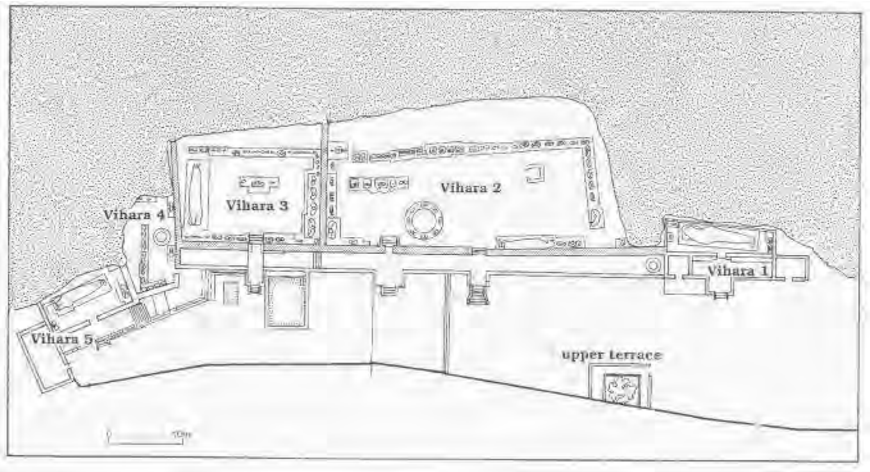

Figure 5, near right
The interior of Vihara 2. The large central panel on the rock ceiling depicts the Buddha's first sermon in the deer park at Isipatana, surrounded by a Thousand Buddha sequence.

Figure 6, far right
Polychrome sculpture and painted walls and ceiling in Vihara 2.

Figure 7, below
Painted rock ceiling of the "ambulatory" of Vihara 2.

Figure 8, below right
Polychrome sculpture and painted rock ceiling of Vihara 2.

boulders on mountain slopes, they consist of clusters of artificially deepened natural shelters with screen walls, lean-to roofs, and deep drip ledges cut into the rock face just above the roofline. A distinctive feature of many of these monasteries is inscriptions carved below the drip ledge. Originally fashioned as residences for communities of Buddhist monks, the monasteries were subsequently developed into elaborate architectural complexes with rock temples, boulder gardens, and freestanding monuments.

A pan-Asian architectural genre

The Sri Lankan rock shelter monasteries are among the earliest examples of a distinctively Asian type of rock-associated religious monument—more than 80% of them Buddhist in origin—whose evolution and typology have

been studied very little from a comparative, pan-regional perspective. In India alone, there are about twelve hundred rock-cut sites, some of which—like Dambulla—have more than fifty individual rock shelter or grotto units.

Although these various rock temple sites belong to a broadly similar genre, there is considerable typological variety and differentiation between them. Present conditions and the problems of conservation and management probably vary more widely than those involved have even begun to realize.

Basic problems

The basic problems relating to rock temple sites in Asia are the very large number of sites that exist—many in places difficult to access—the inadequate knowledge of these sites, and resource inadequacies. As far as many countries in the Asian region are concerned, "resource inadequacies" involve at least seven major factors:

1. Survey and research; i.e., inadequate overall survey, documentation, registration, and mapping of sites; and an even greater inadequacy of research
2. Policy prioritization, including recognition of the importance of even "unimportant" sites
3. Appropriate institutional formation and development
4. Human resources: scientific leadership and technical, research, and managerial personnel
5. Infrastructure
6. Funding, especially sustainable and continuing funding, particularly with regard to tenured or self-sustaining employment possibilities and regular material supplies
7. Continued training and retraining of personnel and upgrading of investigative and conservation technology and equipment

In formulating the management policy and structure of the Dambulla Cultural Triangle Project, which began in 1982 and was scheduled for completion in 1996, every attempt has been made to address these general issues as much as to the specific problems of site management, research, and conservation.

The Cultural Triangle Project

The Cultural Triangle Project in Sri Lanka is a joint Unesco–Sri Lankan program, involving the investigation, conservation, presentation, and management of five of Sri Lanka's seven World Heritage Sites. The following discussion highlights some of the program's main features in terms of the general issues listed.

The most distinctive feature of the Cultural Triangle Project is that it involves, in the Sri Lankan context, an entirely new type of institutional arrangement, which brings together government administrators and

technical experts, university specialists, and private architectural consultants working in association with the temple authorities.

Thus, three or four groups cooperate, while each retains its own authority. This makes for a complex and polycentric institutional structure, whose advantages are (1) the release of a large number of creative energies in the formulation of policy and the implementation of various aspects of the project, and (2) the safeguards provided by a multiplicity of viewpoints in an area of activity where there can be irreversible consequences.

An annual review by a joint Unesco–Sri Lankan Working Group monitors the progress and development of the project. By this mechanism and the participation of international specialists from time to time, the project is able to measure internal standards against international norms where national expertise or resources are inadequate.

Equally important aspects are university-based and internationally collaborative research and training programs, which use the project and the surrounding area as a laboratory and a field school for developing studies of the total archaeological landscape and for the conservation of murals.

Contemporary Dambulla is an urban center with modern services and communications that give the project a good infrastructural base. A major shortcoming is an adequately equipped conservation laboratory, but this is part of a wider situation that is being currently addressed at a national level.

Restorationist traditions and religious requirements

As Dambulla is a living site, the conservation and management of change involves addressing long-standing restorationist traditions of periodic refurbishing (as acts of piety or repair) and changing religious requirements. In Sri Lanka, as in many other cultures, it is traditional to renew wall paintings, as well as to refurbish and add architectural and sculptural elements according to changing religious requirements, artistic fashions, and availability of resources. This process has gone on at Dambulla over several centuries; but, significantly, major changes had not taken place since the 1930s.

In fact, in recent decades the temple authorities at Dambulla—unlike at many other ancient Sri Lankan sites—have upheld a modern conservationist ethic. They argue very forcibly that the preservation of the present character of the site is entirely a result of their millennia-long guardianship of Dambulla. Also, they have readily accepted the heritage management plan of the Cultural Triangle Project and form the critical factor in its implementation.

One specific example is the outcome of a long debate among the project authorities on whether to remove the modern veranda facade at Dambulla and replace it with a wooden colonnade in an eighteenth- to nineteenth-century style, on the basis of somewhat inadequate early photographic documentation. The temple authorities themselves provided the clinching argument that the existing facade at Dambulla was part of the

history and contemporary image of the monument and, as such, should be preserved in its existing form. It can be said that Dambulla, as it appears today, is exemplary as one of the major religious sites in Sri Lanka that has not suffered uncontrolled modernization, vulgarization, or change. This is a result of the interaction between the resources and sensitivity of the Cultural Triangle Project's conservation program and the temple authorities who have supported and participated in it.

Above all, the standpoint and advocacy of the temple authorities has been the vital factor in deciding that the murals at Dambulla, however badly damaged, should be conserved in keeping with modern conservationist principles, rather than with the traditional process still observed at a number of temples where ancient murals are retouched or repainted to make them presentable and readable.

Conservation Strategy

The basic conservation strategy at Dambulla has been to tidy up and maintain the site as it existed at the beginning of the project, while at the same time reorganizing its service infrastructure and presentation.

On the upper terrace and along the main approach, unsightly accretions have been removed, traditional hand-cut stone paving replenished, and an improved water supply and a modern but discreet lighting system installed. At the base of the rock, the bazaar area around an ancient, sacred bodhi tree has been relocated and the tree shrine restored in the form of simple but classical stone-and-sand terraces. In the southwestern sector, excavations have been carried out in the ancient rock-shelter complex and freestanding monastery, and the plain and multiperiod brick structures of the monastery have been conserved. The modern temples along the main trunk road, on the boundary of the protection zone, have been brought into the conservation and layout plan. New religious buildings and a museum to house copies of paintings and archaeological artifacts have also been located here, and plans are under way for off-site parking and a service and shopping precinct.

Mural conservation

The major portion of the conservation program at Dambulla is focused on its murals. By comparison, the murals at Dambulla are much more recent and less extensive than those at Ajanta, and they cover less than one-tenth of the painted area of those at Dunhuang, but they are still one of the largest preserved groups of late-period rock and wall paintings in the South Asian region outside the Himalayan zone. The murals belong to a pan-regional tradition that extends across South and Southeast Asia, especially in Southern India, Sri Lanka, Burma, and Thailand. Dambulla is undoubtedly one of the finest and most impressive expressions of this tradition.

The paintings, which are inside the five main rock temples, belong almost entirely to the post-classic Central Kandyan school of the late eighteenth century. This school of painting derives its name from the city

of Kandy, capital of the last Sri Lankan kingdom of the seventeenth to nineteenth centuries, now also a Unesco World Heritage Site. Fragments of much earlier painting are found just below the drip ledge, outside the present facade, while the presence of an earlier layer of painting below the present painted surface is seen in a few areas and still awaits detailed investigation.

The eighteenth-century murals form the most important artistic heritage of Dambulla. They constitute more than 80% of the surviving paintings, about three-quarters of which are in an excellent state of preservation, covering an area of approximately 3,044 m^2, incorporating the five shrines. The largest of the shrines is Vihara 2 (Figs. 5–8)—an elaborate complex of paintings, sculpture, and architecture and one of the most ambitious undertakings of the Kandyan artists. Vihara 3 is the next in size and retains its eighteenth-century character. Each of the three smaller shrines (Viharas 1, 4, and 5) has been substantially retouched or repainted or, as in the case of Vihara 1, is in a poor state of preservation.

The paintings consist of mineral and organic pigments[1] laid on top of kaolin (a word derived from "Kao-ling," a hill in Jiangxi Province in southeast China, where this fine white clay was originally obtained), the paint-receiving layer. The kaolin is laid on a mud-plaster ground applied to the rock or wall surface. The mud plaster has organic admixtures and a plant-gum glue, probably derived from the sap of the wood apple (*Feronia elephantum*) (Weerasinghe 1987).

The major conservation problems at Dambulla (Fig. 9) are:

1. Deterioration of the pigmented surface and the plaster, evidenced by the detachment of the plaster from the rock surface and of the paint layer from the plaster, and the flaking and powdering of both these elements—damage probably caused by expansion and contraction due to thermal and humidity

Figure 9
Conservation problems: detachment, water seepage, salt efflorescence, biological growths, insect damage, and darkening of the surface by soot from oil lamps.

variations in addition to "material fatigue" factors, which are poorly understood
2. Water seepage through the rock ceiling (treated in some areas over the centuries by the painters themselves who painted non-iconic scenes, such as fish in water and floral awnings, which could be easily retouched or repainted), resulting in salt efflorescence on the surface
3. Biological growths and biodeterioration, caused mainly by fungi and encouraged by the humid conditions and the high sugar, or carbohydrate, content of the binding medium
4. Insect damage in the form of nest building on the painted surface or by penetration into the plaster
5. Human damage caused by devotees and visitors touching the painted surface or by soot from oil lamps (the lamps are no longer a problem, but the damage still needs rectification)

One of the major problems for conservation of the site, not just at Dambulla but on a national scale, is inadequacy in four general areas: skilled human resources, institutional frameworks, policy prioritization, and resource allocation. These factors are all necessary in dealing with mural and polychrome sculpture conservation programs in a situation where there are, in a preliminary listing, more than 650 freestanding and rock temples with paintings in need of conservation.

Early mural conservation measures that had been taken at Dambulla in the pre-1983 period, since about the 1960s, mainly involved (1) cleaning with a xylene and ammonia solution in water, (2) application of a protective coating of polyvinyl-acetate emulsion, and (3) removal of insect nests. The basic strategy of the present Cultural Triangle Project's mural conservation program has been to emphasize investigation, protective conservation, and urgent remedial measures rather than cleaning or reintegration. The work undertaken can be summarized as follows:

1. Investigation: detailed graphic documentation of present condition; environmental monitoring; research (still underway and not conclusive) into plasters, pigments, biological growths, and insect varieties and behavior; monitoring of water seepage through the rock ceiling
2. Protective conservation: early steps to prevent the use of oil lamps inside the shrines; humidity control by improved ventilation measures; attachment of door screens made of netting to inhibit insect entry; measures to deflect water seepage where possible
3. Remedial intervention: consolidation of plaster and paint layer by the application of adhesives and consolidants—mainly, the acrylic emulsion Primal AC33 to fix the plaster support to the rock surface, and Paraloid B72 as a consolidant; removal of insect nests; vacuum cleaning of dust, especially on horizontal surfaces of statues; removal of old polyvinyl-acetate coating

4. Cleaning and reintegration: very little cleaning and reintegration has been undertaken, as it was felt that this was not an urgent measure, and there is no attempt at this stage to fully reintegrate the painted area
5. Training and human resource development: since its inception, the project has paid special attention to training and upgrading and to the development of institutional measures to remedy the national shortage of scientific workers at all levels, especially by combining the training program with project implementation
6. Copying: a copying program, in which the entire complex of paintings is being copied on canvas, is nearly complete and will be displayed and archived in the museum for information and study. The copies are not reconstructions; rather, they document the murals in their actual condition at the present time

Sculpture

Dambulla also has an extremely rich collection of sculpture, both rock-cut and molded in clay and plaster (Figs. 6, 8). This consists largely of iconic representations of the Buddha, rarely bodhisattvas and gods, and three rare portrait sculptures. The statues have a kaolin or lime-plaster finish and pigment. They are basically in a fairly stable condition and have almost inevitably been repainted in relatively recent times. Other than regular maintenance and cleaning, they cause no great problems of conservation.

Note

1 The principal mineral pigments are red cinnabar (mercury sulfide, HgS) and orpiment (arsenic trisulfide, As_2S_3) or realgar (arsenic sulfide, As_2S_2), which give red and yellow pigments, respectively. The blue is thought to be derived from the blue indigo dye obtained from species of *Indigofera,* chiefly *I. arrecta, I. sumatrana,* or *I. tinctoria.* Yellow is mostly obtained from gamboge, the latex extracted from the bark of *Garcinia morella.* Black is from lamp black, often derived from burning cotton rags or from the sap of the jackfruit *(Artocarpus integrafolia).*

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Site-Management Lessons from Canyon de Chelly, Lascaux, Sigiriya, and Bamian

Jeffrey W. Cody

When planning for effective conservation of grotto sites, such as the Mogao grottoes at Dunhuang, China's regional authorities and the State Bureau of Cultural Relics might consider some of the site-management practices adopted by other countries to protect their historic grottoes. This article will outline four of those lessons: (1) exercise caution with regard to premature public access; (2) balance local site control with central government assistance; (3) monitor environmental conditions frequently; and (4) be cautious about any conservation intervention.

These lessons are suggested by the management of four widely dispersed grottoes. Nearest to China are the Buddhist sites of Bamian, an area of intense Mahayana monasticism from the third to the eighth century C.E. in northern Afghanistan; and Sigiriya, a Theravada site from the fifth century C.E. in central Sri Lanka. The planning associated with the Paleolithic cave of Lascaux near Montignac in southwestern France and Canyon de Chelly, a U.S. National Monument in Arizona, also has relevant implications. The underlying argument is that historic grotto sites require not only conventional site management but also more specialized monitoring because of their inherent physical conditions, their often remote geographic locations, and the intense tourist-economic implications associated with the uniqueness of grotto sites.

One area exemplifying this uniqueness and remoteness is Bamian (near Shahidan), Afghanistan, 130 km northwest of Kabul and 2,600 m above sea level in a narrow valley at the foot of the Hindu Kush Mountains. Chinese explorers Faxian in the fifth century C.E. and Xuanzang in the seventh century wrote about Bamian as both a commercial and religious center, a site that reflected Buddhism's expanding appeal throughout Central Asia, noted as early as the first century (Grousset 1971). By the seventh century, Bamian had ten Hinayana monasteries whose monks, since at least the third century, had excavated and painted scores of grottoes in the hillsides for monastic cells (Hackin and Carl 1933; Tarzi 1977). Most of these caves have been destroyed, some by Islamic marauders in the eighth century, others by Genghis Khan in the early thirteenth century, and still others by

Afghan rebels as recently as the early 1980s ("Vasari" Diary 1981:14). Before the more recent turmoil in Afghanistan, the most compelling monuments in the region for tourists were the two standing Buddhas, one 53 m and the other 37 m in height, carved into the valley's cliffs. Xuanzang related how impressive these were when they were gilded over a chalky plaster, a covering that has since entirely eroded (Grousset 1971:82).

Bamian's grottoes share a cultural affinity with the Mogao grottoes near Dunhuang. The two sites' similarity regarding tourism also merits consideration. The Royal Afghan Government constructed a small tourist center at Bamian in the mid-1970s after a team of conservators from India assisted in the site's consolidation (Sengupta 1971). The encouragement the Afghan government implicitly provided to tourists to visit Bamian at a time when tourism was at a peak in Afghanistan demonstrates a first site-management example: to be cautious about attracting tourists if the site will suffer because tourist visits are not supervised properly. In Bamian, the government accommodated tourists, on the one hand, by building a small visitor center and by permitting locals to open guest houses; while, on the other hand, it insufficiently protected the site from tourists, who were allowed for a fee to explore at will and, all too often in the 1970s, to hunt for souvenirs. Even before the civil strife that began in the 1980s, there was no on-site interpretation to help visitors truly understand the site they were experiencing.

Bamian also provides a second lesson: the need to facilitate communication between national and provincial decision makers (including military forces), all of whom ideally should collaborate regarding conservation policies and enforcement. From the late 1970s to the present, Bamian has suffered from military conflicts because the grottoes have been used as places of refuge and have been in the line of fire.[1] Occupation of the Mogao grottoes by Russian soldiers early in the twentieth century is a reminder that, despite geographic isolation, historic grotto sites sometimes unpredictably fall prey to military use. Furthermore, the actions of those wielding power over cultural property at the local level, such as those granting building permits for Bamian guest houses in the mid-1970s, sometimes contradict the intentions of those making decisions at the national level, such as the officials who decided in Kabul in 1969 to cooperate with Indian conservation experts.

Sigiriya, near the archaeological sites of Anuradhapura and Polonnaruwa in the so-called cultural triangle of north-central Sri Lanka, is a site that corroborates another of Bamian's site-management lessons: Be cautious about attracting too many tourists too soon. Rising 200 m above a lush plain, Sigiriya is a steep mound with a summit covering 1.6 ha, where King Kassapa constructed a fortress palace in 477 c.e., from which he ruled for seventeen years. During that period, the king ordered that Buddhist figures, or *apsaras*—some patterned after contemporary Gupta murals in Ajanta (India)—be painted in shallow niches created by overhangs below the summit (Paranavitana 1961). Of the several hundred apsaras that once filled these tempera paintings, only twenty-two survive.[2] The apsaras are somewhat protected from atmospheric damage because of the overhangs

and from human contact because they are out of reach; the frescoes remain largely in the open air and thus are susceptible to damage from humidity and vandalism. The most significant act of vandalism occurred in mid-October 1967 (Udalagama 1970), when vandals climbed halfway up the rock, daubed green commercial paint on several of the wall paintings, scratched out portions of two figures, and stabbed a third panel with a pointed instrument.

At Sigiriya, although there is no tourist center and only a few interpretive signs, the central government has taken measures to bring tourists close to the monument. Furthermore, hundreds of local religious devotees visit the site regularly on certain days according to the lunar calendar. Brick steps have been constructed near massive sculptures of lions' feet at the base of the mound, stone steps have been created by chiseling into the mound, and metal walkways have been attached to ledges to allow for closer access to both the rock paintings and the summit. While these additions have facilitated visits for tourists (despite no guardrails at the summit), they have brought so many tourists so close that the site has suffered, as can be seen in weakened, rusting metal steps and railings.

If Sigiriya's lesson for Mogao is to be wary of too much tourism too soon, then the question raised by the experiences at both Sigiriya and Bamian is how one can shut off the tourist faucet once it has been turned on. The Mogao grottoes' administrators should not look to any one particular case for an answer to this question. However, what has occurred at two other sites provides some insight about how to consider the question. Although geographically removed from the Asian context, Lascaux and Canyon de Chelly yield lessons that resonate for Mogao because of their longer track records as grotto sites of international historic significance.

Discovered in 1940, the multichambered cave of Lascaux contains some of the most memorable examples of European Paleolithic art (10,000–20,000 B.P.). The site is one of approximately 140 such grottoes in France and one of 280 European prehistoric grottoes (Leroi-Gourhan 1979). Lascaux was open to the public until 1963, when deterioration was deemed so severe that the site was closed to tourists (Froidevaux 1955; [Daniel?] 1963). The French Ministry of Culture decided to stabilize the grotto's climate and then to continue to monitor that stability, and to restrict access to similarly threatened sites such as Les Eyzies-de-Tayac-Sireuil (Aquitaine).

To mitigate public outcry, the Ministry then decided to reproduce significant portions of the rock arts (Faux Lascaux 1972). The reproductions were housed nearby in a special center, affording visitors a vicarious pleasure in an appropriate context (Delluc and Delluc 1984). The success of this approach has led to similar ventures in Germany and Japan (Ministère de la Culture et Conseil Général de la Dordogne 1990:41). In taking these measures, the French Ministry demonstrated a recognition that it had erred in allowing too much tourism too soon. To remedy this mistake, the national government allocated resources, communicated with provincial and local councils, and responded effectively to tourist needs. The rationale of the French Ministry to put a premium on site conserva-

tion by climatic control at the expense of universal public access is a site-management lesson that Mogao administrators are heeding: the new tourist center at Mogao opened in 1994 and features reproductions of some of the Mogao grotto paintings. However, one of the ironies of Lascaux is that by protecting the site, the government has mummified it. This action, then, calls into question the logic of accepting Lascaux as the ideal model for grotto site management.

Finally, the management of the Canyon de Chelly National Monument in northeastern Arizona not only confirms the lessons indicated by the previous three cases but also underscores other lesson, particularly from a policy point of view. Canyon de Chelly National Monument, established in 1931 on the Navajo Reservation and Trust Lands, comprises three steep-walled sandstone canyons. More than one thousand rock art sites are included within the monument's boundaries, most of them from the Anasazi culture of 700–1300 C.E. (U.S. Department of the Interior 1989). The Navajo Nation practices traditional activities—such as grazing livestock, farming, and hunting within the monument area; access to the site for non-Navajos is normally limited to the White House Ruins trail. In the past decade, several unresolved issues have illustrated that despite more than sixty years of site "protection" site management at Canyon de Chelly is far from ideal. Four salient issues, as they relate to the Mogao grottoes, are the following:

First, how should the protection of the historical ruins be reconciled with the interpretation of the ways of life of the Navajo today? Resolution of this question would imply significant changes to the visitor center and relevant interpretive programs. Of relevance to Mogao might be first to consider how the Buddhist nature of the site relates to ethnic minorities living in Gansu Province today, and then to interpret those relationships for visitors with appropriate signage and written information in several languages.

A second significant issue at Canyon de Chelly is how to better define and enforce the vaguely articulated boundaries of the monument. To resolve this would imply the allocation of more government staff and resources in a time of budgetary reductions. In light of this problem, Mogao's managers today might well consider the issue of site boundary carefully because of what it implies for future managers who will inherit today's definitions.

Third, administrators at Canyon de Chelly are asking how to prevent damage to the site from heightened commercial and residential development. Despite the remoteness of the monument when it was established, only six decades later the area is coveted by private companies for its raw materials and by tourists for its pristine location. Mogao policy makers might heed this lesson as well, especially in the context of current provincial disputes about illegal dumping of toxic wastes (Yeung 1993).

Finally, Canyon de Chelly administrators are considering the question of how to avoid overlapping jurisdictions among the National Park Service, the Bureau of Indian Affairs, and the Navajo Nation. Too much inaction, duplication of effort, and misunderstanding have resulted from

not knowing who should decide questions regarding land use, trespassing, vandalism, and site conservation. Although Mogao's administrators might be relieved to hear that the United States, too, has serious problems regarding one work unit's control over another unit's actions, the lesson is that the site ultimately suffers unless questions of jurisdiction are resolved early and, in an ideal sense, amicably and comprehensively.

What, then, are the four crucial site-management lessons suggested by Bamian, Sigiriya, Lascaux, and Canyon de Chelly?

1. Don't be seduced by the economic benefits of tourism by allowing access too soon. All of the sites outlined above have had to modify their policies regarding human contact with their grotto sites. Careful planning now will save money, and better protect the site, for the future. Prepare for the unpredictable. Provide more interpretive material for tourists, rather than less, respecting their desire to understand the site even if they are not permitted universal access.
2. Balance local site control with central government assistance, specifically determining who will handle each issue. Bamian illustrates that the scale is tipping toward localism; Canyon de Chelly shows what can occur when too much jurisdiction is exercised by overlapping national agencies; Lascaux demonstrates an attempt at finding a middle ground.
3. Monitor the grottoes' physical condition as often as feasible, and correct problems as soon as possible. Today's solutions (allowing visitors in Lascaux, or constructing metal stairways in Sigiriya) might well become tomorrow's problems.
4. Because each grotto site is unique, each solution requires careful study before intervention. Because there is no single model to follow, there is a need to be flexible and vigilant. Based on the consideration of site-management lessons gleaned from four sites on three continents, Chinese administrators should strive for careful site management with distinctive Chinese characteristics. What are those characteristics? That is for the Chinese to decide.

Notes

1 In the fall of 1993, an unnamed cultural affairs officer at the Embassy of Afghanistan in Washington, D.C., verified that Bamian had suffered an unspecified amount of damage from military activities. Because of "more pressing social needs," he said, no comprehensive survey of the damage has been conducted. For an earlier indication of damage to Afghan historic sites during the recent civil turmoil, see "The 'Vasari' Diary" 1981:14.

2 As reported by Udalagama (1970), Khan Ullah, an Indian chemist, determined in the early 1950s that the tempera paintings had originally been applied to a trilayered surface consisting of (1) a plaster of liver-red alluvium, vegetable fiber, and rice husk on the rock surface; (2) a composition of sand, clay, lime, and vegetable fiber; and (3) a sand and lime mortar.

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The Role of Documentation in Defining Conservation Strategies at Grotto Sites

Stephen Rickerby

THE FIRST and most important step in the conservation of any cultural site is to collect and analyze information about its physical history and present condition. Documentation plays a critical role as a tool for decision making, particularly in relation to the often insurmountable deterioration problems that affect cultural sites. Confronted by these threats, the limitations of many physical conservation interventions are apparent, though often only after ineffective interventions have been made. The main aim of documentation should be to provide information that can forestall such mistaken interventions in the future by identifying, if possible, exact sequences and rates of decay over time, thus helping to establish what can and cannot be safely treated in the long term.

Documentation Strategies

Defining appropriate conservation strategies with documentation as a basis was the focus of a two-week training course, "The Management of Grotto Sites," held at the Yungang grottoes in Shanxi Province in October 1992, organized by the Getty Conservation Institute with the State Bureau of Cultural Relics of the People's Republic of China. The course was organized around a step-by-step planning process to introduce the principles and practices of systematic site management to a group of site managers, conservators, conservation scientists, and other specialists from grotto sites all over China.[1]

Advances in science and technology are currently being applied to the preservation of China's grotto sites at an unprecedented rate. The situation was somewhat different in 1983, when Luo Zhewen of the State Bureau of Cultural Relics summarized the problems facing such sites:

> In tackling the destructive factors of nature, such as the wind and rain, sunshine, moisture, lightning and thunder, earthquakes, insects, micro-organisms and so on, which keep on corroding and damaging historical relics by weathering stone carvings, discolouring mural paintings and deteriorating organic materials . . . we need advanced science and technology. However, many

> technical problems have not yet been solved, and demand our further efforts in this area (Bourke et al. 1983:45).

The scientific and technical advances now available are to be welcomed, but the direction in which conservation endeavors can be pushed by such developments should also be questioned. The recent history of site conservation in the West is replete with interventions motivated by the intention to arrest decay permanently; this has proved a challenging task indeed, often with disastrous consequences. An example was the widespread policy of detaching wall paintings from their cultural sites in order to preserve them in museum environments. Such interventions have irrevocably altered the original sites of these paintings and inflicted massive damage on the paintings themselves; in many cases, deterioration has only been hastened in the museum environment.[2] With hindsight, it is possible to say that better prior documentation could have led to better-informed strategy decisions and reduced the likelihood of such catastrophic interventions.

In current practice, however, documentation acquired by scientific investigation is put to many uses, both beneficial and otherwise. Analysis is used advantageously, for example, to increase the scant knowledge of original materials and techniques employed in the construction and decoration of grotto sites. Such information is of value in its own right yet can also have conservation implications. At Yungang, for example, a recent investigation of the sculptural polychromy of Cave 6 has highlighted the deterioration of lead-containing pigments as a factor that affects the preservation of the site (see Piqué herein). Rarely, however, is such documentation actually used to prevent or restrain inappropriate interventions. Typically, treatment is considered an unavoidable choice at threatened cultural sites, a predetermined course of action that is reinforced by acceptable prior documentation—"acceptable" in this context meaning documentation that is selected to justify an intervention.

The reasons for this prevailing scenario are partly understandable, though in the long term hardly justified. Certainly, cultural sites such as grottoes are faced with major problems of decay. At Yungang, for example, exposure to harsh environmental conditions has exacted a relentless toll on the sandstone rock. Situated in one of the largest coal-producing areas in China, the Yungang grottoes is subject to airborne pollution that has in modern times exacerbated deterioration; an estimated two thousand uncovered coal trucks pass along the main highway in front of the site daily (see Christoforou et al. herein). Cultural sites worldwide are affected by problems of similar severity, to which may be added a newer range of threats in recent years associated with mass tourism. At the Longmen grottoes in Henan Province, for example, visitors now number more than a million per year, of whom some fifty thousand are foreigners; the record for a single day was seventy thousand, when the pressure on the site approached intolerable limits.[3]

Confronted by such problems, managers and others responsible for the protection of cultural sites find themselves under intense pressure

to take action in the form of physical interventions. In many cases, this is supported by copious data from prior documentation processes. Cultural sites of international renown are the subject of repeated investigations and studies, often under the auspices of prestigious conservation organizations. A familiar refrain is that enough long-term documentation has been done and that the time to intervene is now, before these cultural monuments become little more than a memory.

But how accurate is this diagnosis? Without belittling the seriousness of many known problems affecting cultural sites, it is often the manner in which threats are perceived rather than a true assessment of their nature that becomes an impetus for conservation interventions. Frequently, too, these perceptions are motivated by external events that take little account of the individual circumstances of a particular site. An example is the introduction of legislation for preserving cultural monuments, which is typically matched by an upsurge in conservation interventions. No one would dispute the necessity of such legislation, but in providing the opportunity to intervene, this decision is too often made without regard for the real needs of a particular site.

What are the real needs of a threatened cultural site, and how should they be assessed? These questions were explored during the Yungang training course, when participants were asked to report on the condition of some of the more seriously deteriorated painted caves and to assess their current conservation needs. Basic condition surveys were made using photographs or baseline drawings superimposed with transparent sheets to record graphically the different categories of damage and decay. Exposed to severe weathering, the caves showed clear evidence of salt efflorescence and crust formation, rock splitting and exfoliation, and pigment loss; and the initial consensus of opinion was that they required urgent physical interventions to stem these manifestations of decay. In the case of one of the grottoes examined, historic photographs were compared with the cave's present condition. The course participants were surprised that decay had not progressed in any major visible form over a period of about twenty years; the one area of dramatic alteration was the clearing of the floor level, undertaken during a recent archaeological excavation, which had exposed more deteriorated portions of the rock walls.

These simple exercises highlighted the main assumptions and discrepancies in the way decay is frequently perceived by those who care for cultural sites. The *appearance* of decay is taken as proof of progressive or alarming deterioration demanding urgent attention. In turn, manifestations of decay are too easily linked to specific causes that in reality are complex and interrelated and that remain misunderstood, even as decisions are made to undertake major physical interventions. Whereas many forms of natural decay are insidious and gradual, human actions that we often imagine as beneficial—conservation interventions, archaeological excavations—can cause dramatic and sudden alterations of far greater impact to cultural sites. This neither suggests that environmental threats never have sudden consequences nor underestimates natural decay mechanisms. The effects of inexorable weathering are obvious at many grotto

sites in China, especially as seen in efforts made in the Ming and Qing dynasties, when attempts were made to restore eroded carvings with modeled mud plaster. But in assessing the present condition of a cultural site, all causes of change must be examined—including the conservator's own interventions and activities.

Conclusions

The comprehensive documentation of cultural sites is too often neglected in favor of other forms of immediate intervention. What is required is much more broad-based documentation, providing information on the earliest known physical condition of a cultural site and all subsequent alterations to its context, fabric, and other internal features. Achieving these goals is not difficult, though analysis of collected data is more complex. Information can be derived from many and varied sources: archaeological data, historical photographs, archival and conservation records, oral histories, et cetera. Combining this information with ongoing site documentation—photographic surveys, graphic condition reports, inventories, and other relevant materials—constitutes a comprehensive record that should be used as the basis of all decisions regarding site preservation.

Advances in science and technology also offer opportunities to enhance documentation and contribute to the improved diagnosis of problems of decay. An example is the development of computer-image processing and digital documentation, enabling accurate and quantifiable analyses of change and decay (Esposito and Vitolo 1989:347–58). Increasingly, conservation science should be applied to the study of sequences and rates of change over time, not just to current manifestations of decay and proposals to intervene in them.

Whether documentation is conducted by traditional methods, with the aid of modern technology, or a combination of both, it is essential that records are retrospective and ongoing. The importance of correlating information from current investigations with data from the physical history of a site cannot be underestimated. It is the only means of assessing whether decay is past, current, or progressive; avoiding repeating previous mistaken interventions; informing decisions regarding the need for maintenance rather than higher levels of intervention to limit future deterioration; and, if new interventions are necessary, providing a sound basis on which to make appropriate treatment decisions.

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Notes

1 The training course was coordinated by Margaret Mac Lean, formerly Training Program senior coordinator at the Getty Conservation Institute and now director of the Documentation Program there. The instructors were Sharon Sullivan, director of the Australian Heritage Commission, and the present author. For a fuller discussion of the course curriculum, see Sullivan herein.

2 For a discussion of the detrimental effects of wall paintings detachment, see Torraca 1983:1–18.

3 Statistics supplied to the GCI Training Program by the Longmen grottoes site staff.

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Conservation Survey of the Tam Ting Caves

Benita Johnson

Figure 1
View of the limestone cliff housing the Tam Ting caves as viewed from across the Mekong River.

Containing thousands of sculptures of the Buddha, the Tam Ting caves consist of two limestone caves, upper and lower, situated on the west bank of the Mekong River in the Lao People's Democratic Republic (Lao P.D.R.). Tam Ting is an active Buddhist shrine and also one of the nation's major attractions for both Lao and foreign visitors (Fig. 1). Unfortunately, however, a growing number of tourists to the site has dramatically increased the potential for damage to the caves and their sculptures. Theft and a lack of security, inappropriate past restorations, the growth of mold, and infestation by wood borers, termites, and bats have all contributed to the deterioration of the caves.

Following a survey of conservation needs in Southeast Asia in 1990, Andrew Durham, then head of conservation at the National Gallery of Australia, suggested that the caves warranted an extensive conservation project but cautioned that there would be practical, ethical, and logistic difficulties associated with it (Durham 1991:37). He envisaged the project as having several progressive stages, the first of which was completed in October 1992.[1] The objectives of Stage One were to

- identify and assess the nature of the site and its contents with particular reference to conservation and management parameters (including the range of artifact materials and techniques represented),
- survey the major physical features of the site and the spatial characteristics of its assemblages,
- outline the broad conservation and management issues,
- determine priorities for future conservation and project works, and
- provide a set of interim management recommendations.

Cultural Context

Religion

Today, approximately half of the population of Lao P.D.R. are Theravada (also known as Hinayana) Buddhists. Many sources state that Buddhism

was introduced to the region between the sixth and eighth centuries C.E.; there are grottoes in Lao that are thought to have been used as Buddhist shrines from the ninth to tenth centuries (Vistarini 1993). It is commonly believed that Buddhism reached Lao from India through Burma, Thailand, and Cambodia. Over the centuries, the religion has greatly influenced the values, customs, and behavior of the Lao people.

Prior to the introduction of Buddhism, animist beliefs and ancestor worship predominated. These beliefs, known as Phi, still survive among several of the ethnic hill tribes in northern Lao, as well as through myths and legends of present-day seasons and festivals. The practices of Phi are thought to have benignly coexisted with those of Buddhism until the sixteenth century, at which time Buddhism was declared the state religion in Lao by King Fa Ngum, the first monarch of Lan Xang.

Although officially banned, Phi still remains the dominant non-Buddhist belief in the country, frequently existing parallel to and/or in combination with Buddhism and Brahmanism. The Tam Ting caves illustrate this point, as the caves contain at least one Phi figure—a guardian figure in the upper cave (Fig. 2)—and several cast-cement Ramayana figures in the lower cave, in addition to the thousands of sculptures of the Buddha.

The Buddha sculptures

The focus of Lao traditional art has been religious; since the fourteenth century, it has been primarily Buddhist and heavily influenced by Thai culture and its artistic styles (Seckel 1968:62). The Tam Ting caves contain sculptures that stylistically represent Lao, Thai, and some Chinese forms, with differences in robe and headdress types, suggesting a chronology of styles. The sculptures range from larger than life-size statues to smaller than finger-length figurines (Fig. 3).

Figure 2
Guardian figure of the upper cave, unique in that it is the only sculptural form carved directly from the limestone bedrock.

Figure 3
Sculptural group, showing the size and number of sculptures as seen from the interior of the lower cave.

Lao sculpture of the sixteenth to eighteenth centuries, at the height of the kingdom of Lan Xang, is most distinctively Laotian. Sculptures were usually made of bronze, stone, or wood; and the subject was invariably the Buddha. In the Tam Ting caves, most of the figures were carved from wood, but a few were also fashioned out of tree resin (sometimes covered with silver sheeting), horn, and ceramic. A few bronze sculptures may still be found in the caves, although most of these, as well as gold and rock crystal sculptures, have been removed since 1975. Virtually all the sculptures found in the caves are lacquered and gilded. The lacquer applied was usually black, but sometimes red lacquer was added over the black. Like other Buddhist sculptors, Lao artisans emphasized features thought to be representative of the historical Buddha, including a beaklike nose, extended earlobes, tightly curled hair, and so on.

Two types of standing Buddha images are distinctively Lao. The first is the "calling for rain" posture, which depicts the Buddha standing with hands held rigidly at his sides, fingers pointing toward the ground. This posture is rarely seen in other Southeast Asian Buddhist art traditions. The flat, slablike earlobes, arched eyebrows, and aquiline nose are uniquely Lao, as is the commonly upward-curled bottom hem of the Buddha's robe. Many sculptures of this style are found in the Tam Ting caves.

The other original Lao image type is the "contemplating the bodhi tree" Buddha. The bodhi tree, also called the "tree of enlightenment," refers to the large banyan tree in Bodhgaya, India, beneath which the historical Buddha was said to have been sitting when he attained enlightenment in the sixth century B.C.E. In this depiction, the Buddha is standing in much the same way as in the "calling for rain" pose, except that his hands are crossed at the wrist in front of his body. Very few examples of this form are found at Tam Ting.

Although not uniquely Laotian, the Tam Ting caves contain many sculptures of the Buddha seated in the "calling the earth to witness" position—his left hand in his lap and his right hand palm down over his knee. Another style found in the caves is the "meditation" position, with the Buddha sitting cross-legged with his hands cupped, palms upward, in his lap. A rarer form depicts the Buddha walking. A sculpture of the Buddha lying on his side depicts the Buddha in death, but this form was not observed in the Tam Ting caves.

Buddhist sculptures in Lao are not found only in temples or shrines. They also are found on high shelves, or altars, in homes and shops.

Environmental Context

Climatic factors

Lao is in the tropical monsoon zone and has two basic seasons: the wet monsoon from May to October and the dry season from November to April. The province of Luang Prabang receives an average rainfall of 1,000–1,500 mm a year. The coldest time of year is from December to January, the height of the dry season, when nighttime temperatures drop to 5–10 °C. In the wet season, daytime temperatures reach 25 °C.

During the seven days of the site visit discussed here, outdoor relative humidity varied from 76% to 91%, with temperatures ranging from 10 °C at night to 20 °C during the day. Rain fell constantly for six consecutive days.

Relative humidity readings for the upper cave decreased from 83% just inside the entrance to 72.5% at the back of the cave. The lower cave recorded readings of 80% to 69% RH from the front to the back of the cave, respectively.

Wildlife

Poisonous tree snakes and centipedes are common around the Tam Ting caves. A python was said to live in the lower cave but was never seen by project members. Wasps and bats, which present distinct conservation problems, are found in both caves. Although crocodiles and tigers were common to the region until approximately twenty years ago, neither inhabits the area today.

Site Description

Tam Ting consists of two limestone caves within a low but locally prominent limestone hill, situated on the west bank of the Mekong River and immediately downstream of the mouth of the Ou River, latitude 20°2′, longitude 102°13′. The fishing village of Pak Ou faces the caves from the opposite side of the river and is approximately 35 km upstream from Luang Prabang. The majority of the limestone hill supports a tropical mesophyll forest cover with a tall woodland structure.

It is thought that until the early part of the sixteenth century, the caves were used as a sacrificial site for the many hierarchical Phi gods, which were believed to watch over the people. From the sixteenth century until 1975, the royal family, who lived in Luang Prabang, often visited the caves and used them as a Buddhist shrine for worship, coronations, annual New Year's festivals, and the end of the wet-season boat races. A natural spring found at the lower cave was the source for sacred water, having been used in coronation ceremonies. The royal family commissioned their own artists and artisans who produced sculptures for the caves, while the monks from Luang Prabang maintained the shrines. As of this writing, only one royally commissioned sculptor, in his eighties, survives. Regrettably, the arts of carving and gilding are rapidly disappearing in Lao, although some monks still apply gilding to wat (Buddhist temple) exteriors in Luang Prabang, and the resurgence of these arts is being encouraged in the fine arts schools of Vientiane and Luang Prabang (Vistarini 1993).

Traditionally, there were separate areas in the caves where only men were allowed, and women were forbidden to touch any of the sculptures. No one was allowed to wear shoes or hats inside the caves. Today, however, these restrictions do not seem to apply, and local men even smoke in the caves.

As the caves are active Buddhist shrines, both contain remnants of incense sticks, withered flowers, and other plant material, particularly in front of the altarlike sculptural groupings. Both caves contain evidence of human cremation remains (Fig. 4).

A dominant visual feature of both caves is the major sculptural groupings containing numerous Buddhist figures. There are approximately four thousand upright, relatively intact figures in both caves; yet, according to local people, this represents only about one-quarter of the sculptures that were present before 1975. The figures are predominantly made of wood covered with lacquer, which in turn has been covered with gold leaf. Sculptures and artifacts made of bronze, ceramic, resin, silver, and horn were also noted. The majority of the sculptures are not permanently installed and are easily moved. Photographs of the lower cave in the late 1960s indicate that significant rearrangement of sculptures has occurred since that time (White and Garrett 1968:765).

Based on the interpretation of stylistic criteria and a limited number of inscribed dates, the sculptures appear to date from at least the seventeenth to the twentieth century, with the majority displaying stylistic traits suggesting eighteenth- and nineteenth-century origins. The state of preservation of individual sculptures does not seem to reflect their age; rather, the materials of their construction, location in the caves, and previous history of usage and handling have contributed to their deterioration.

There is considerable evidence of the restoration and maintenance of the caves and their sculptures over an extended period of time. A plaque found near the mouth of the upper cave states that some restoration of the caves' contents was carried out in 1932 and advises that the king will punish anyone caught defacing the sacred site.

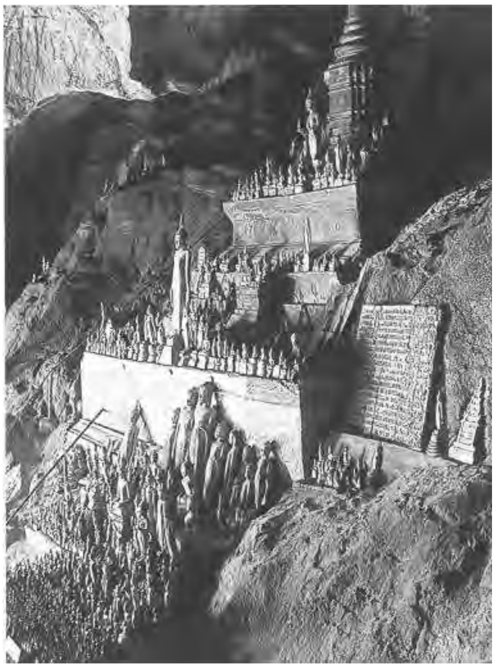

Figure 4
Some cremations are found in association with the sculptures. Note the stupa at the top of the cave.

The assemblages of Buddha sculptures and the riverside cave context provide Tam Ting with its major tourism appeal; paradoxically, these same features and their potential for tourism present the greatest challenges for the conservation of the site.

Upper cave

The mouth of the upper cave is located two-thirds of the way up the hill, approximately 50 m above the Mekong River on a steep slope to the south of the riverside cliff. A continuous path and series of stairs provide access from a separate river landing. Although sometimes quite steep, the stairs on this route (241 steps from the river level at the time of this survey) are in relatively good condition and are kept quite clear of vegetation.

These stairs and the path from the lower cave meet at a junction where a covered eating area has been built to accommodate site visitors. A short walk away from the covered area is a toilet block. In addition, a garbage dump is situated in a small gully close to the block, consisting primarily of refuse from packed lunches, most notably nonbiodegradable plastics. Exposed to wind dispersal and to wildlife, the dump is having an increasingly negative impact on the visitor areas.

Another covered eating area with an adjacent single toilet block, added in 1993, is located just below and to the north of the upper cave entrance. Wooden tables and chairs are located in the eating areas, but water must be carried up to the site from the river below.

The upper cave has a predominantly level floor, extending for 55 m into the dark interior, and reaches an approximate maximum height of 20 m (Fig. 5). The interior consists of a level and continuous series of caverns and broad passages culminating in two large caverns. As with the lower cave, cave development is limited and currently inactive. The upper cave appears to contain an extensive deposit of accumulated sediments, including pockets of alluvially derived clastic fills and a potentially extensive archaeological deposit.

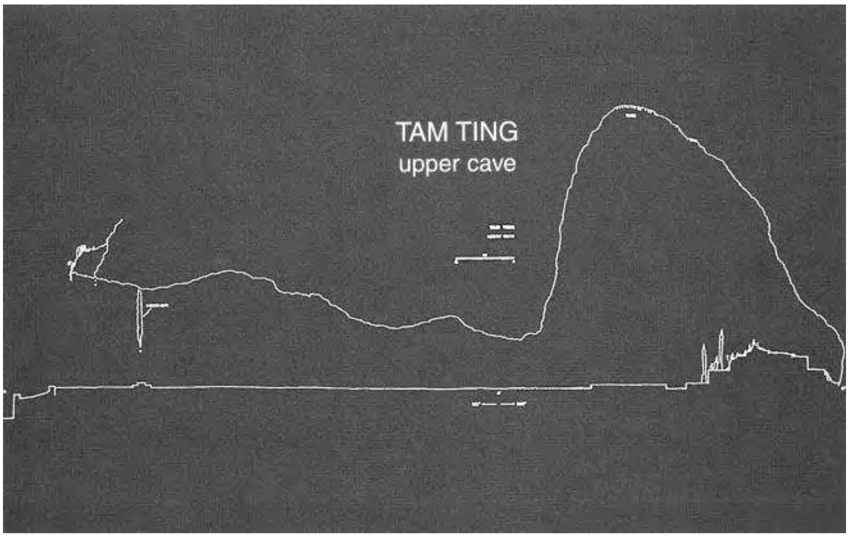

Figure 5
Approximate cross section of the upper cave.

A considerable time period and occupational history is indicated by the cave's built features. Various brick platforms and wall complexes occur throughout the cave, most notably in side niches and the end caverns. The entrance to the cave has two large wooden doors behind an open iron grillwork grate, topped with an intricately carved wooden lintel; the lintel and doors are reported to date from the nineteenth century. The lintel still contains traces of polychrome paint and gilding but also suffers from much termite attack. Although the iron grate is locked at night, access is still available into the cave through small side openings or over the top of the iron grate. Consequently, the cave is not secure from intruders. The sides of the gates have been stuccoed and contain some relief carving, although much is now missing. A large, Chinese-style Buddha is located outside and to the right of the entrance (Fig. 6). Small niches in the limestone surrounding the entrance contain small Buddha sculptures. Some tree roots have grown around the cave entrance from the forest that grows above it. Several benched garden beds are situated on both sides of a rectangular entrance platform and stairway.

The upper cave is deeper and higher than the lower cave and has a relatively flat floor. The largest and highest portion of the cave, at its distal end, is home to a small colony of bats, their presence being most noticeable from their odor, noise, and droppings. A guardian figure has been carved out of the parent limestone and is located close to the interior mouth of the cave. It is believed that such figures watch over the rains and rivers, in addition to protecting entrances and stairways of shrines (Naenna 1990:3). With the exception of this figure, no carvings of the actual limestone walls are found. However, rock art—in the form of painted or stenciled gilt images, resin applied in low relief, and writing—is found on the rock walls. Some of the written material appears to record the presence of contemporary visitors; attempts have been made to scrub these marks off the walls.

Figure 6
Entrance to the upper cave, revealing nineteenth-century lintel, recent iron grillwork, and Chinese-style sculpture.

Figure 7
Cave interior with visitor candles, the use of which is damaging the sculptures. Note incense behind the front sculpture.

Figure 8
Entrance to the lower cave from the Mekong River.

Figure 9
Eroded pathway joining the two caves.

Carbon residues are found on the walls and ceilings, and lumps of wax are found on ledges in front of sculptural groupings. These are all residues from the use of candles, which both worshippers and other visitors use to illuminate the cave (Fig. 7).

It is unclear what exactly had been restored during the 1932 intervention recorded by the plaque at the entrance to the upper cave. Several sculptures were noted to have been broken and then repaired in the past; many of these repairs in the upper cave are of high quality, although the adhesives used are unknown. In general, the condition of the sculptures in this cave is much better than of those in the lower cave, despite the fact that some of the upper-cave sculptures are older. Based on stylistic attributes and inscriptions, the sculptures date from the seventeenth to the twentieth century, most having been made in the eighteenth and nineteenth centuries.

An approximate count of fifteen hundred intact sculptures was made in the upper cave. This number is only an estimate and does not include most of the sculptures toppled over in the rubble or individual figures found in scattered niches.

Lower cave

The mouth of the lower cave forms a prominent landmark visible from the river and is situated in the basal portion of an extensive vertical riverbank cliff line (Fig. 8). Access from the river, adjacent to the cave mouth, is provided by a series of steps (thirty-six from the river level at the time of this survey). Here the river is considerably deeper than the downstream landing, making loading and unloading more problematic. A pathway adjoins these stairs with the stairs to the upper cave; parts of this pathway and associated steps have eroded down the hillside and are hazardous to path users (Fig. 9).

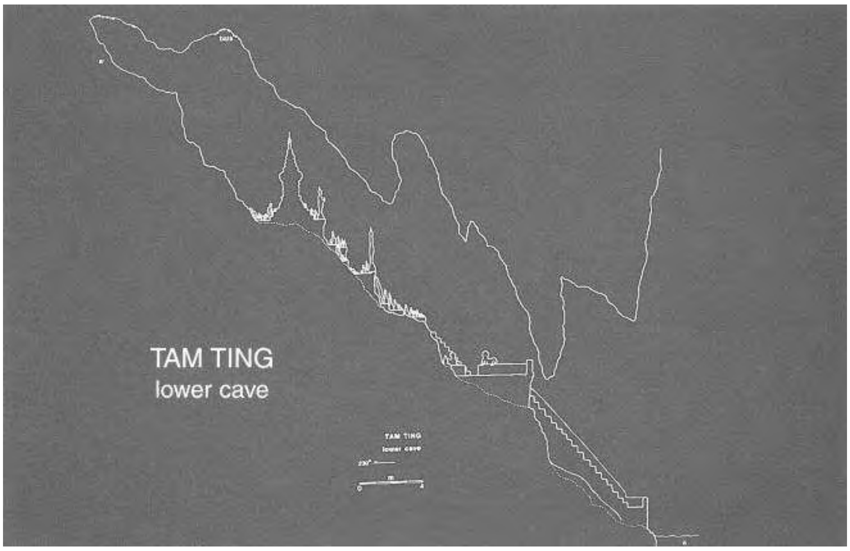

Figure 10
Approximate cross section of the lower cave.

Figure 11
Main area of worship in the lower cave.

The lower cave is steeper and more shallow than the upper cave, with a steeply inclined natural floor, consisting of flowstone and bedrock features, that descends to the level of the Mekong River at the mouth of the cave. The cave extends for approximately 35 m from the entrance with a similar maximum width and height at any one point of around 15 m (Fig. 10). As the cave is comparatively shallow, natural daylight allows viewing of most of the interior. Limestone development is limited to extensive flowstone deposits, associated columns, and pool deposits. Apart from isolated drips, the cave appears relatively dry.

An altarlike arrangement of sculptures is the focal point of the lower cave. This grouping is closest to the river's edge and has a flat cement platform in front of it that serves a religious function: most worshippers leave offerings of flowers and incense here (Fig. 11).

A series of retaining walls, staircases, and platforms has been constructed to provide both an open, level space near the cave mouth and a sequence of smaller joined or isolated rectangular platforms on which to place sculptures of the Buddha. A large stupa (dome-shaped Buddhist shrine) is situated on the highest platform. Cast-cement sculptures depicting figures from the Ramayana are found throughout the lower regions of the cave. On the lower platforms, the cast-cement figures and associated architectural features are regularly whitewashed, with some smaller features having been recently painted in red enamel paint. Two small reliefs depicting lizards or crocodiles have been cemented onto a limestone wall near the front entrance. A sign reading "spring" in English points to the right side of the cave. Although a water source was not located by the survey team, it may be a seasonal spring, since it is well known that these waters were used in royal coronation ceremonies.

Most Buddha sculptures found in the lower cave date from the nineteenth century. Recognizable standing sculptures number approximately twenty-two hundred.

The lower cave also exhibits more recent intervention. In addition to the recent painting of architectural features and non-Buddhist sculptures, many of the figures have been cemented into the limestone rock in an effort to prevent theft. In some cases, all that now remains are hardened lumps of cement containing wooden stub remnants. Further intervention took place in conjunction with the Princess of Thailand's visit. To improve safety for the royal party, bamboo railings and posts were embedded into concrete blocks set directly into the limestone foundation. The extent of rock markings on the walls is less than in the upper cave, although the range of types is similar. Both bats and wasps inhabit this cave.

Limitations of the Survey

Several factors limited the scope and degree of the initial fieldwork. On-site fieldwork was conducted for seven of the fifteen days allocated to the project; the remaining time was spent in transit and conducting necessary liaison and support work. The Princess of Thailand's visit, which took place during the site survey, precluded any work in the caves on that day. The unanticipated requirement for overnight stopovers to ensure flight connections within Lao also significantly reduced the available time on-site. As a result of these factors, photographic coverage of the sites was conducted at a preliminary level only, and the mapping of the lower cave was done quickly, resulting in varying levels of accuracy.

A lack of knowledge of the Lao language, culture, and Buddhist beliefs predicated the type and level of understanding achievable regarding the cultural context and dynamics of the site. The historic and contemporary oral information gained during fieldwork can therefore be considered only as dependent primary data rather than corroborated information.

Although the fieldwork provided a reliable assessment of the physically definable environmental and management constraints of Tam Ting, the survey had neither the time nor human resources to assess the contemporary human values associated with the caves. As a result, information is limited regarding factors such as the level of local, provincial, and federal managerial participation; the use of economic resources; and the Lao cultural values of the site.

In keeping with the preliminary and assessment nature of this initial survey, the use of sophisticated equipment and materials was kept to a minimum. This ensured flexibility within the potential constraints of unknown site contexts and facilities. Time limitations also precluded the opportunity of sending supplies in advance. Finally, six days of mud-producing rain and the inevitable stomach ailments common to foreign visitors, which were also suffered by the Lao team members, made the working conditions less than ideal. The resulting documentation of Tam Ting should not, therefore, be considered comprehensive or systematic beyond the requirements of the survey's objectives.

Interim Recommendations

The survey produced suggested measures to protect the caves and their contents until further conservation methods could be implemented. The

recommendations, submitted to the Australian Department of Foreign Affairs and Trade in a report dated 19 November 1992, were as follows:

1. Site visitors should be directed not to touch or handle the Buddha sculptures. Reasons for this instruction should be given. Site managers and custodians should touch the sculptures only when absolutely necessary and should refrain from moving the sculptures from their current locations. The majority of the sculptures in Tam Ting have suffered extensive borer and termite attack, leaving them extremely fragile. In many cases, it is only the very thin layers of lacquer and gilding that hold the figures together. Lifting a sculpture by the head or arm is likely to result in breakage. Unfortunately, this type of inappropriate handling and consequent damage was witnessed several times during the six-day period despite attempts at prevention. Every time an object is handled, its rate of deterioration is increased and the stability of exceedingly fragile pieces is threatened.
2. All of the floor and wall deposits should be protected from impact. There should be no further disturbance to the cave floors by digging or implanting objects within them. The deposits in both caves appear to have major potential as an archaeological and scientific resource and should be conserved for future research.
3. No further sculptures or nonarchitectural artifacts should be fixed in place or restored using cement. Several sculptures have been cemented in place in the lower cave. Aside from the detrimental effects concerning preservation, it has proved to be ineffective in deterring the deliberate breaking off or accidental damage of sculptures (as evidenced by several lumps of cement with sculptures missing).
4. The removal of graffiti from the walls of the cave should not be attempted until adequate methods are devised and an appropriate survey and recording of the rock markings is carried out. Some graffiti may prove to have historical or cultural value, while the act of using solvents and abrasives may further damage associated rock art and its substrate.
5. The use of enamel paints, and any painting in the interior of the caves or of the wooden entrance to the upper cave, should not be allowed until the appropriate paint types and techniques are defined. An unknown type of white paint, possibly whitewash, is regularly applied to the architectural and some in situ sculptural features in the lower cave. Buddha sculptures in close proximity to these painted walls have been splattered with the paint, creating serious conservation problems for those pieces (Fig. 12). It may, however, be considered necessary by Lao site custodians to repaint some of the whitewashed areas within the lower cave. In this event, care must be taken

Figure 12
Result of recent whitewashing in the lower cave.

in any future application of whitewash to avoid all surfaces of the Buddha sculptures and to apply paint only to those walls and features (non-Buddha sculptures and architectural elements) already painted and maintained in this way. Portions of the platforms in the lower cave have also been painted with red enamel paint. More stringent precautions must accompany the use of this paint. Should any of this paint inadvertently land on the sculptures, it will be difficult to remove in the future.

6. Smoking and littering within the caves should be prohibited and this policy posted and enforced by tour guides.
7. The on-site disposal of garbage created by tourists needs to be improved. The present surface dump located adjacent to the lower toilet block contains numerous nonbiodegradable materials, including a multitude of plastic trays that are gradually being dispersed over the wider region. The dump is visually obtrusive and may seriously threaten the quality of visitor experience in the near future. It is suggested that the surface dump be replaced with a disposal pit and that the existing garbage be buried. In the future, tour guides should be responsible for taking their groups' garbage back with them to Luang Prabang (i.e., taking away everything they brought to the site, including lunch remnants and all disposables). Tour groups should be discouraged from using synthetic plastics.
8. Installation of electric lights in either cave would be detrimental to the preservation of the site and should not be considered as a visitor-management option. Electric lights would increase ambient temperature intermittently, and hence create fluctuations in relative humidity, a cause of damage to artifacts. Plant nutrients, in the form of dust and bat droppings, exist within the caves. Increased light levels could consequently promote the damaging growth of organisms. In addition, greater illumination of the sites may not be necessary to provide a rewarding visitor experience. Several visitors to the site commented on the appropriate ambience of the dark caves and the use of candles in the upper cave. It is suggested that the cultural value of the ambient and traditional light sources be explained and promoted by tour guides (Fig. 13). The use of handheld torches (flashlights) is to be encouraged.
9. Visitors should not be allowed access to the caves without an appropriate tour guide or government representative. Guides should not leave a cave until all members of their group have left. Visitors should only be allowed on pathways and staircases, and they must be advised not to climb on the platforms or the limestone formations.
10. It is important that, prior to entering the cave sites, guides explain conditions of entry to members of their tour group, as well as the conservation reasons for these restrictions.

Figure 13
Cave interior, showing ambience created by visitor candlelight.

11. It is highly recommended that each tour group be limited to ten to fifteen people, with a minimum of one tour guide per group per cave. The lower cave, in particular, cannot safely accommodate more people than this at any one time, and greater numbers would not allow for a full appreciation of the nature of the site.
12. To aid visitor safety, it is recommended that the pathway leading from the lower eating area to the lower cave be leveled and reinforced. Parts of the path and associated steps have eroded down the hillside and are potentially hazardous to path users.
13. It is recommended that rainwater be collected, particularly at the upper cave, for human use. At the time of the site visit, water was being manually carried up from the Mekong River to service both toilet blocks.
14. It is suggested that translations of this document be circulated to all relevant bodies associated with and/or responsible for the management of Tam Ting, including the Lao Office of Tourism. Translated copies of these recommendations should be provided and explained to all on-site workers and tour guides at Tam Ting.

Recommendations for Future Site Management

It is further recommended that the following steps be taken to encourage the future preservation of the caves:

1. Site security should be significantly improved.
2. Authorized site-specific interpretive signs, ideally in several languages in addition to Lao, should be installed along the pathways and near the designated eating areas of the site. These signs should not obscure the features of the site or impede photography; they should, however, be illustrated and cover the subject matter succinctly (Lambert 1989:37).
3. Simple brochures or leaflets providing site-specific information should be made available for sale at the site. Studies have found that the most effective method of disseminating this

information is for official guides to sell printed literature at a nominal fee, in person, to the visitors.

4. A visitors' book and pencil should be kept at the caves to reduce the risk of site graffiti. Guest books can offer an alternative to vandalism, as they have shown to be effective as an outlet for graffiti and offensive comments.
5. Visitor access to the site should be restricted to built-platform viewing areas, not the use of the limestone formations as platforms or areas within hand's reach of the sculptures. Low barriers, possibly using natural plant-fiber rope or bamboo fences, might be effective psychological deterrents to touching or picking up sculptures.
6. Bats and wasps should be removed from the caves and kept out by the use of screening material. First, however, the bats should be identified to determine if they are an endangered species.
7. Samples of the platform brickwork should be inspected by a conservation architect to determine the need for their replacement. They appear to lack cohesion and strength, thereby endangering the Buddha sculptures.
8. Graffiti should be identified and removed appropriately.
9. Further research should be undertaken on the religious and cultural significance of the site and the art history of the caves' Buddhist images. There is also a need for further research to determine where the majority of the caves' sculptures have been relocated.
10. Samples should be taken of sculpture materials (i.e., lacquers, gilding, and the various substrates, such as wood, bronze, resin, horn, and ceramic) and then analyzed for exact composition. Although not directly relevant to the management program of the site, information derived from these analyses can greatly assist in future conservation treatment, art and archaeological studies of the area, and methods of manufacture (Fig. 14).
11. Small wooden carvings should be sold as souvenirs at the entrance of the caves. Although images of the Buddha may be found for sale in the markets of Luang Prabang and Vientiane, this practice is frowned upon by devout Buddhists. It is therefore suggested that the local villagers of Pak Ou be encouraged to carve images of Phi figures or to imitate some of the caves' architectural features and sell them to Tam Ting visitors. This would provide the villagers with additional income as well as reduce the risk of cave-sculpture theft.

Figure 14
Figure repaired using identifiable fragments.

Postscript

Since this paper was presented in 1993, the project team, including staff and students from the University of Canberra, as well as federal and provincial staff of the Lao Ministry of Information and Culture, have returned to the site in 1993, 1994, and 1995. Some of the aforementioned

recommendations have been implemented, while others continue to be addressed. Site work has been concentrated primarily in the upper cave, where the main worshipping area is being partially excavated and restored. The project is scheduled to continue for the next two years.

Acknowledgments

Funding for this conservation project was generously supplied by the Australian Ministry of Foreign Affairs and Trade and the Lao Ministry of Information and Culture. The project staff would sincerely like to thank Michael Mann, former Australian ambassador to Lao, and Thongsa Sayavongkhamdy, director-general of the Lao Department of Museums and Archaeology, Ministry of Information and Culture. For the 1993–95 seasons, the author's gratitude is extended to her esteemed colleague Brian Egloff, also of the University of Canberra, and the Lao team members representing the federal and provincial departments of the Ministry of Information and Culture. Last, warm thanks are extended to the local Council and the people of Pak Ou who good-naturedly put up with foreign idiosyncrasies and put great effort into welcoming the project staff into their homes and lives.

Note

1 The project was headed by the author in cooperation with Kelvin Officer, consulting archaeologist at Navin Officer Archaeological Resource Management. Assistance in administration and fieldwork was provided by Bounheng Bouasisengpraseuth, deputy director of Museums and Archaeology, Ministry of Information and Culture, Vientiane; and Somboun Bounthavong, Division of Cultural Affairs, Luang Prabang. Translation was provided by Bounheng Bouasisengpraseuth.

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KEYNOTE ADDRESS

Complexity and Communication: Principles of In Situ Conservation

Sharon Cather

As the objectives of conservation evolve from remedial treatment to preventive intervention, new challenges emerge. This is particularly true in the field of in situ conservation, where the numbers, size, and widespread distribution of sites and buildings—coupled with the diversity of their ownership and use—compound the difficulties of problem solving and decision making. Recognition of past failures in conservation and of the present inadequacy of our understanding of both decay mechanisms and potential remedies should lead to far more caution. Problem solving needs to focus on disentangling complex effects from multiple causes. This requires a shift in funding away from treatment in favor of investigations of monitoring and diagnosis—a leap of confidence, as it requires a deferral of immediate, visible results in favor of long-term, intangible ones. Decision making depends on bridging the communication gap between a bewildering range of technical experts and the beleaguered nonspecialist administrators who still, remarkably, make all the main decisions about conservation. And this requires that conservation specialists provide candid, well-argued, and viable alternative options for addressing complex problems.

The inexorable trend toward increasing complexity in conservation has important implications. Current efforts to understand the nature of materials, the processes of deterioration, and the intricate relationships between effects and causes have led to a proliferation of the disciplines involved in conservation and a shift toward a scientific basis. These developments are both inevitable and desirable.

But what are the implications of this trend? Although there are many, this chapter will concentrate on just two. First, improved knowledge of materials and of decay mechanisms should have a direct bearing on principles and practices: we should be more cautious. Second, the results of multidisciplinary problem solving should be comprehensible to those outside the individual disciplines involved: we[1] should communicate better.

The discipline of conservation has evolved only recently. It has developed from the care of museum collections of fine art—that is, accumulations of discrete objects separated from their cultural and physical

contexts; housed in structures in which the causes of deterioration can, to a greater or lesser extent, be controlled; and maintained where the objectives of treatment are narrowly and unilaterally defined, nearly always by the curators.

But conservation in situ (for the purposes of this discussion, the focus is on the conservation of wall paintings) is an altogether different matter. It demands a reassessment of the objectives and approaches borrowed from museums. Preservation of cultural property in situ differs fundamentally from care of collections in a variety of ways: in scale, location, ownership, and hence use; and—perhaps most problematic of all—in the complexity of monitoring, diagnosis, and intervention.

The scale of the problem is partly a matter of the actual size of individual "objects." The area of the paintings recently conserved on the cupola of the cathedral of Florence is greater than that of all the paintings in the National Gallery in London combined; yet even this vast project is in turn dwarfed by the magnitude of the paintings of the Mogao grottoes at Dunhuang.[2] The scale of the problem is also one of number. Overall numbers are difficult to assess, primarily because of the lack of adequate inventories of cultural property. In England, for example, a country not normally considered rich in mural painting, an inventory begun in 1980 and still ongoing has established that there are more than two thousand buildings with medieval wall paintings. Another problem that characterizes in situ conservation is location. Sites are always dispersed and often remotely situated, and the paintings themselves inaccessible. Moreover, the buildings are likely to be in use—often in a way that is inimical to the goals of conservation—and controlled by owners (private, institutional, corporate, ecclesiastical, or governmental) for whom conservation may not be a high priority.

The technical complexity of conservation in situ is obvious merely from a glance at the contents of this volume. There seem to be two principal reasons for this increasing complexity. First, through recognition of the persistent failures of treatment in the past, we have become more concerned with materials—both the original materials of objects and the materials applied to them. Second, we have realized that because of the risks to objects, the high costs, and the likely inadequacy of treatment, it is better to attempt passive or preventive rather than remedial measures. Neither understanding materials nor designing preventive conservation is easily accomplished, however; both require a firm scientific basis and a range of expertise.

Though all of these aspects of site-based conservation have significant implications, particularly with regard to planning and funding, this paper focuses on the multidisciplinary complexity and the consequent obligation of communication.

Complexity

A single example may serve to demonstrate the present complexity of conserving wall paintings in situ. At Hardham, a remote church in the south of England, the paintings of circa 1100 are in perilous condition: the paint

layer is being pushed off by salts (Figs. 1–5).[3] Because of the importance of these paintings, there is great concern over their deterioration and much pressure to conserve them, despite the fact that the paintings have been "conserved" five times since they were discovered 125 years ago. Although their condition is no doubt alarming, it has been alarming for many years. This is not an emergency; there is time for deliberation and planning. Therefore, what should be done? Moreover, who will decide?

While it is known that salts are crystallizing and pushing off the paint layer (Fig. 5), the first step before any intervention is even contemplated is to establish precisely what is happening and why—to define the effect and determine the cause. To study the salts at Hardham, the following areas of investigation would need to be carried out:[4]

History

A necessary preliminary to any program of investigation is documentary research to establish and assemble what may already be known about the paintings, the building, and any previous interventions.

Present condition

To determine the extent and state of the painting, to characterize the nature and distribution of decay phenomena, and to identify possible later additions requires in situ, noninvasive examination; graphic mapping; and photographic recording.

Original and added materials

From the perspective gained from a condition survey, the original, altered, and added materials should be investigated. This requires

- development of a strategy for both noninvasive and invasive investigation;
- sampling the full range of materials and stratigraphies; and
- analysis of pigments, binders, renders, consolidants, and coatings.

Moisture survey

Since the sources, transport, and behavior of salts are dependent on moisture—both as liquid water and water vapor—a full survey is required, involving

- investigation of the structure to determine the range of materials present and their thermal and hygral behavior, and to clarify the history of alterations to the fabric;
- investigation of the distribution of moisture in the structure, including core sampling to establish a three-dimensional model;
- examination and recording of heating and ventilation, and of rainwater disposal; and
- a minimum of one year of environmental monitoring of exterior and interior ambient temperature and relative humidity,

Figure 1, left
Hardham Church, England, exterior view from the north. This modest building of flint-rubble construction has been altered remarkably little since it was built around 1100.

Figure 2, above
Hardham Church, England, interior view toward the east. The original scheme of painting—Christological and hagiographical cycles—survives almost entirely intact, covering the walls of both the nave and chancel. From iconographical evidence, the painting has been shown to be of circa 1100 and, from architectural evidence, to be coeval with the architecture.

Figure 3, above
Detail of the *Annunciation,* Hardham Church, England. Almost uniquely for English medieval wall painting, the scheme at Hardham seems to have been painted predominantly in *buon fresco,* the orthodox palette only occasionally extending to pigments incompatible with fresco, as in the blue-green halos seen here.

Figure 4, near right
Detail of the *Annunciation,* Hardham Church, England. Both the separate *giornata* (plaster patch) for the head of the Virgin Annunciate and the thick impasto of the lime-white details are clearly visible. Although the green pigment from the halo has been analyzed as a copper chloride, it is not clear whether this is original or an alteration due to contamination with chloride salts.

Figure 5, above
Detail of the *Last Judgment* on the west wall, Hardham Church, England. Soluble salts and organic coatings are responsible for the alarming deterioration shown here. The primary salt damage is from sulfation, while the various coatings applied in past treatments include size, varnish, wax, and soluble nylon.

and of interior surface temperature; followed by calculation of dew-point temperature and absolute humidity, and comparison with information on external weathering exposure and local climate.

Salts

Since salts, in the present case, are the most immediate cause of the deterioration, it is important to establish a clear understanding of their types and distribution in three dimensions in the structure. This requires

- mapping of the actual and apparent salt activity, ideally in different seasons;
- correlation of the salt activity with decay phenomena;
- development of a sampling strategy;
- sampling in three dimensions; and
- qualitative and quantitative analysis of the salts, including those in the building materials.

Although this condensed list could easily be much longer, it could not be much shorter without jeopardizing the likelihood of coming to reasonably satisfactory conclusions. To anyone involved in such an investigation—a phenomenological approach—it will be clear that the division into the categories listed here is for convenience. In practice, each area of study informs, defines, and directs the others. None can be carried out in isolation, and each must take account of the other. This is, of course, far more easily said than done. It also means that although there is a general sequence of investigations, a study cannot be strictly linear. There must inevitably be reexamination, resampling, and reevaluation throughout the process.

Such a diagnostic investigation would require the collaboration of a conservator, an art historian, a conservation scientist, and an environmental specialist, and—for some types of analysis—very probably additional conservation scientists. Yet Hardham is a relatively simple case. Others are far more complex: for conserving the wall paintings of Piero della Francesca at Arezzo, for example, several years and several million dollars were spent trying to answer such questions (Piero 1989).

Communication

Remarkably, it is never these technical specialists who ultimately decide if conservation will actually be undertaken. They advise, they propose, but they do not decide. Such decision making is the province of others, of those charged with the care of the monuments and with the funding of that care. They are most likely to be predominantly art historians, archaeologists, or professional administrators. Therefore, the way results and conclusions of complex investigations are communicated to these decision makers becomes crucial. This conveniently leaves aside the equally difficult issue of how diverse specialists themselves will agree on their conclusions.

Returning to the example of Hardham Church, and assuming that after a year or two of intense investigations the various specialists have reached a conclusion, to whom is it then conveyed? Who will make the decisions? In this particular case—and, indeed, for wall paintings in any church still in use in England—there are a number of official bodies responsible. They are the parish church council (elected members of the particular church, who have legal responsibility for its care); the architect (appointed by the parish to provide overall supervision of the maintenance of the church and its contents); the diocesan advisory committee (a group of professionals that advises the chancellor of the diocese whether proposals that affect a church building or its contents should be approved—a group that, in this particular instance, includes a specialist wall-paintings adviser, though this is rarely the case); the Council for the Care of Churches (an advisory body of the Church of England that is responsible for commenting on proposals and for providing limited funding of conservation); and English Heritage (the national, government-funded agency that would probably be involved due to the importance of the paintings and the likelihood of being approached for funding).

This list is not particularly long, and is probably fairly representative of the range of bodies involved in most in situ conservation programs. Communication between technical specialists and those with the decision-making responsibilities has long been an issue, but the current trend toward passive and preventive conservation has inevitably complicated this process. The reason is fairly straightforward: intervention is not confined to the object itself. In the case of wall paintings, proposals for preventive conservation may include the use of a building (restrictions of visitor numbers, times and lengths of visits); alterations to heating, ventilation, lighting, and drainage; and specifications for building-repair materials and methods, and maintenance. Such proposals, which are both prescriptive and proscriptive, quite clearly cut across the competencies and responsibilities of other professionals such as site managers, architects, archaeologists, engineers, builders, and so on. Moreover, someone else—still not the conservation professional—must reconcile any conflicting interests and responsibilities.

There is one further difficulty with preventive conservation in situ that must be taken into account in this overall decision-making process: we have relatively little experience in predicting the effects of interventions for passive conservation in complex physical systems. Such effects will take some time to be manifest and may be difficult to interpret. Preventive conservation implies monitoring; that is, the measured assessment of the effects over time.

Monitoring has never been popular with those who fund conservation. A preference for clearly visible results—for before-and-after photographs—militates against it. In addition, we are not very good at monitoring; little experience has been accumulated, and few guidelines exist. The systems studied are ones in which there are too many variables and measurement is difficult.

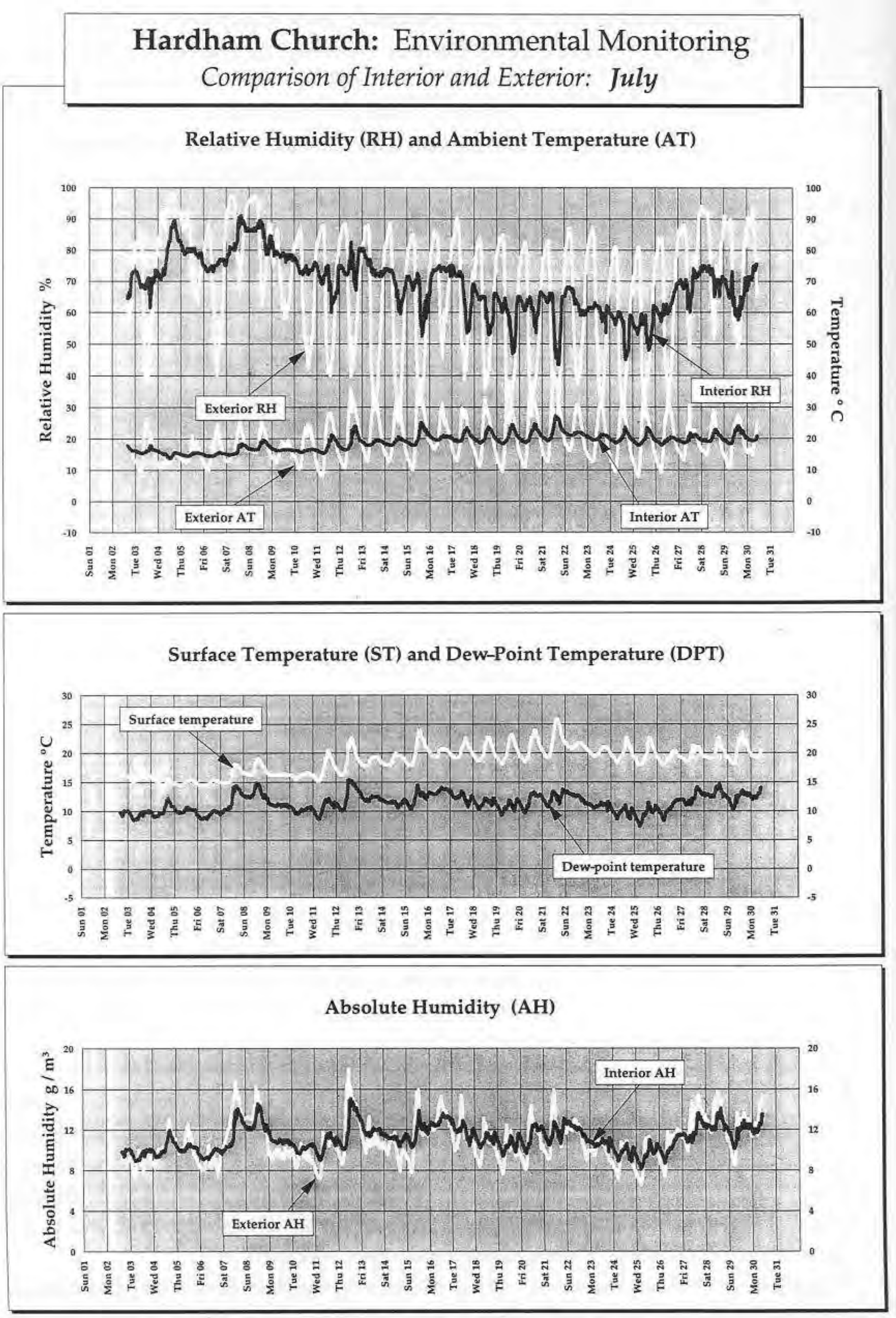


Figure 6
Hardham Church, England, comparison of interior and exterior environmental monitoring for July. Environmental monitoring was carried out to assess the role microclimate plays in activating decay mechanisms (salts and organic coatings). Measured parameters included exterior relative humidity (RH) and ambient temperature (AT), and RH, AT, and surface temperature (ST) at several interior locations. From these, absolute humidity (AH) and dew-point temperature (DPT) were calculated.[5]

What does this mean in specific cases? Returning once more to the Hardham example, results of investigations indicate that excessive ventilation has contributed significantly to salt crystallization by causing large shifts in both relative and absolute humidity (Figs. 6–8). Heating has played

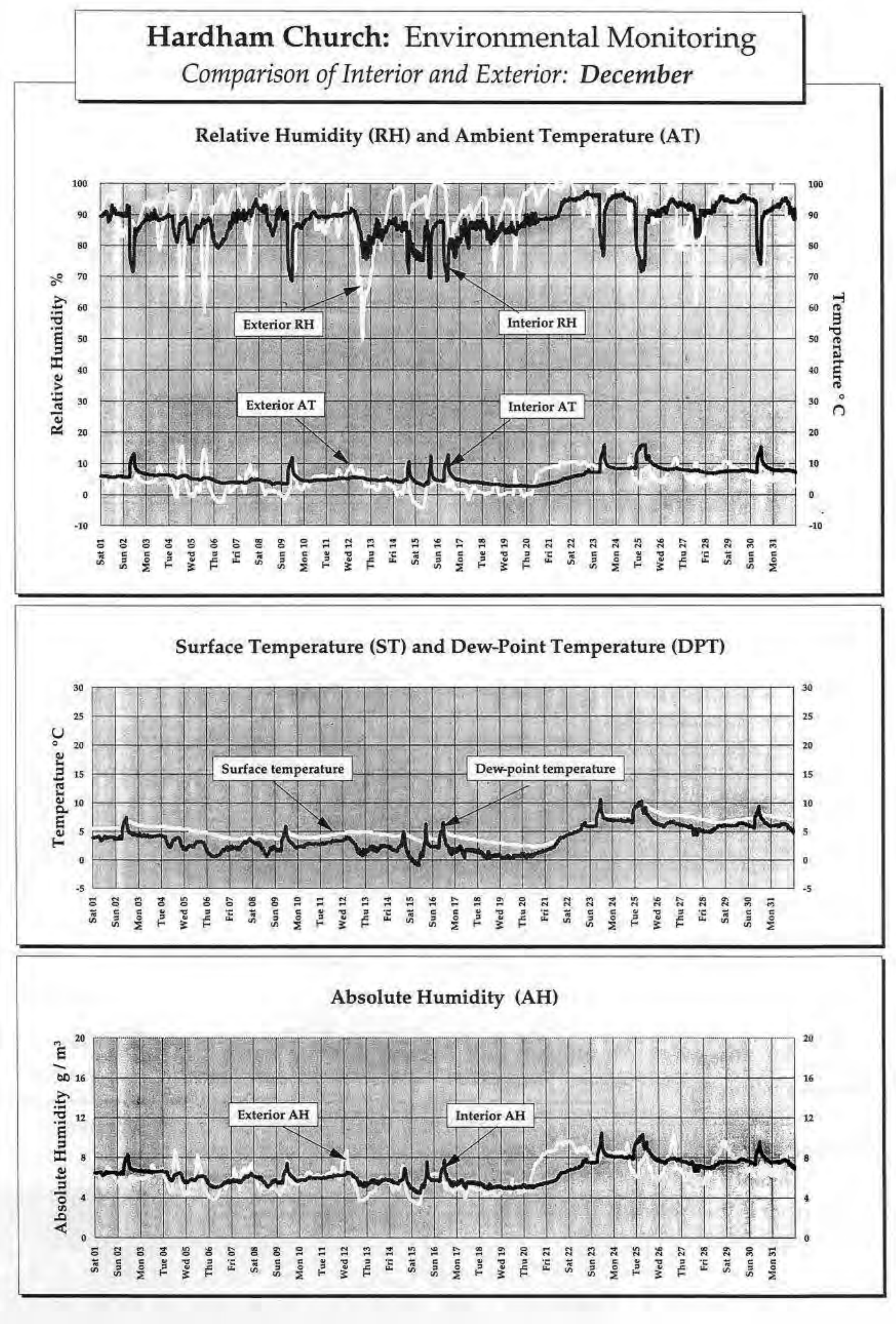


Figure 7
Comparison of interior and exterior environmental monitoring for December.

a role as well. Intermittent use has resulted in short, strong cycles of increased temperature; and, since water is produced as a by-product, temperature cycles are mirrored by increases in absolute humidity (Fig. 9). The resulting frequent episodes of condensation cause dissolution of the

Figure 8
Effects of ventilation in July.[6]

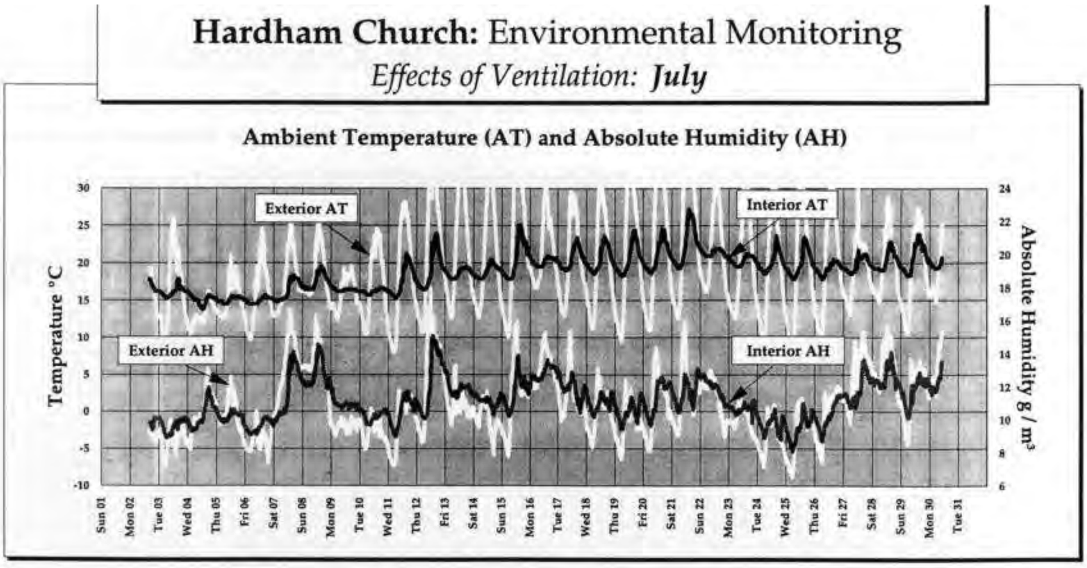


Figure 9
Effects of intermittent heating in December, indicating that heating was causing episodes of condensation.[7]

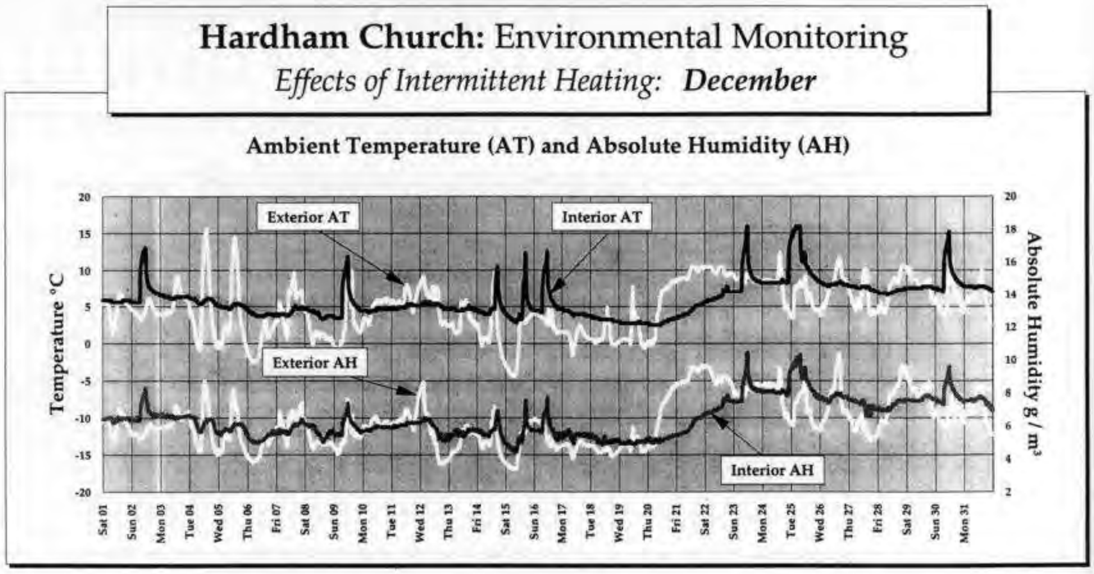
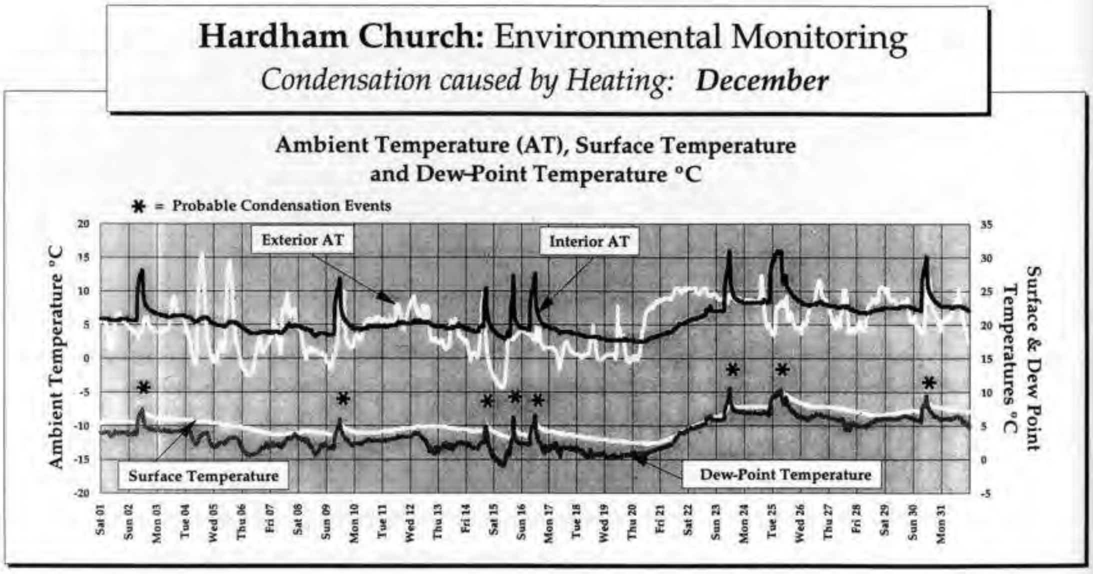


Figure 10
Condensation caused by heating in December.[8]



salts, which then recrystallize when the relative humidity falls (Fig. 10). What, then, should be proposed? Reduce the ventilation and change the heating—two separate variables that contribute to the overall environmental conditions.

This raises a number of questions: How can the effects be monitored? How long is it necessary to monitor, and how much will it cost? How certain can one be of the conclusions? During this period, what happens to the paintings that are in "alarming" condition? Finally, why should the decision makers believe us, since the decision to increase ventilation was itself the result of an expert proposal of some fifteen years ago?

To summarize, preventive conservation in situ is an enormously complex task, involving a wide range of conservation specialists who must reconcile their findings into coherent proposals to be judged by a separate group of professionals responsible for making the overall decisions. It should be added that in certain places and for certain monuments this problem has been overcome through the combination of these two groups into an overall, integrated administrative structure. However desirable, this rarely has been the case.

Remarks

At the outset, it was asserted that we should be more cautious. The foregoing discussion of the particular difficulties of in situ conservation and the present limited state of experience in diagnosis, monitoring, and preventive measures should reinforce that assertion. But there are further compelling reasons for approaching such complex problems with caution:

- Past failures have led to frequent cycles of treatment that are not only harmful to the objects, but a waste of scarce resources.
- The focus has tended to be on the most important objects; this is partly because their significance attracts attention, and partly because we are afraid *not* to intervene, since the lack of sufficient understanding of decay mechanisms leads to a lack of confidence that intervention is unnecessary.
- Symptoms rather than causes tend to be treated.
- Materials continue to be selected on the basis of their working properties rather than their performance characteristics.
- For most treatments to porous materials, reversibility is simply a myth; and effective retreatability is far from assured.
- Conservation is far too subject to fashion, both in the results expected and in the materials used (many conservation treatments can be dated at a glance).

What, then, is needed? It is fairly easy to recite the list of conservation principles—reversibility, durability, compatibility, minimal intervention, and so on—but the focus at present is still on treatment. Until attention is redirected to the causes of deterioration, the cultural

heritage will continue to be overtreated. We must be able to set priorities and target resources.

To be able to set priorities, we must first have a clear understanding of what we have. This means carrying out inventories and documenting condition. These steps must be the basis for any planned program of preservation, and they must be carried out jointly by art historians who understand the relative value of monuments and by conservators who can assess their condition. Then we must be prepared to undertake only the minimum treatment necessary to stabilize those objects that are at immediate risk. The temptation is always to do more.

To approach the overall task of conservation with caution, conservation specialists need to radically improve their methods of monitoring and diagnosis. This should be done jointly by scientists and conservators and would require a shift in funding away from treatment in favor of scientific investigation, since monitoring and diagnosis must be quantifiable. Although it is a common criticism of conservation that it has become too scientific, this is only true insofar as it is sometimes misguided. Much expensive analysis, investigation, and research is carried out without a clear understanding of its relation to genuine conservation issues or without an understanding of the specific questions intended to be answered. In general, however, there is too little recourse to the methods and tools that science can offer. The obvious exceptions are the highly prestigious projects—the Brancacci chapel; the tomb of Nefertari; Piero della Francesca at Arezzo; and, of course, the Mogao grottoes. Such major, costly, concerted programs are indispensable if conservation methods are to progress. Effectively, it is primarily such programs that push forward the boundaries of understanding of materials and their decay in complex physical systems.

And what of communication? It should be clear that if the complex problem solving of in situ conservation is to succeed, it must involve the cooperation of a range of professionals who can communicate with one another. We have been fairly bad at this, and scientists have been the worst. This may be largely a result of the shorthand methods scientists use and the nature of scientific data. Although these are necessary characteristics of the discipline, they can and should be interpreted for the nonspecialist. Everyone should insist on clarity and on an explicit statement of the relevance of any information to the specific problem under consideration. Finally, we have tended to manipulate decision making by artificially narrowing the options, by making single or very limited proposals. Those who are not specialists but who must make many of the most important decisions—whether to intervene, how to intervene, how much funding is available—should be aware of all the options. We should be more candid about the range of ways in which any given problem may be approached and be able to clearly set out the advantages and disadvantages of various options—the first of which, always, is to do nothing.

Notes

1 By "we" is meant *all* those responsible, severally and collectively, for the preservation of our cultural heritage. The burden of responsibility must be shared among specialists and nonspecialists alike, among those trained in conservation and those who may encounter such responsibility only rarely.

2 There is an order of magnitude difference. While the immense Florentine program involved the conservation of some 3,800 m^2 of painting (Acidini Luchinat and Dalla Negra 1995:3), it has been estimated that there are more than 45,000 m^2 of painted surface at Dunhuang.

3 It is also being pulled off by the various coatings that have been applied—size, varnish, wax, and soluble nylon—and damaged by bat excreta, though even these problems are overshadowed by the salt deterioration. On damage to wall paintings from bat excreta, see Paine 1993.

4 The causes of deterioration of the paintings here have been the subject of an ongoing program of study by the Courtauld Institute, including extensive environmental monitoring. Within this project, investigation of the primary deteriogens—deliquescent salts and organic coatings—was undertaken by Alison Sawdy in 1993–94 (Sawdy 1994). Following this preliminary phase of investigation, further research funded by English Heritage is currently being undertaken on the various remaining issues, including biodeterioration, and potential treatment materials and methods.

5 To facilitate interpretation, and to improve communication with nonspecialists, several adjustments have been made in the way that the data are presented. Each page displays an entire month, with both the date and the day of the week, facilitating correlation with the use of the building. The data are presented in three charts: (a) exterior and interior relative humidity and ambient temperature, with the exterior values underlaid as the macroclimate "background"; (b) surface temperature (ST) and dew-point temperature (DPT) to indicate at a glance whether condensation is likely to have occurred—that is, if the DPT exceeds the ST; and (c) exterior and interior absolute humidity to indicate sources of any changes, whether from the external macroclimate or from internal sources. The three charts are aligned vertically so that an event or change in one parameter can be compared to its source or effect in another. For example, the large increase in temperature in the church on Tuesday, 25 December (Christmas day), can be traced in the two charts below as a condensation event (where the DPT exceeds the ST) and as a substantial increase in absolute humidity unrelated to the exterior value, which is actually falling.

6 Medieval buildings are typically efficient climate buffers. By isolating temperature and absolute humidity values in the presentation of monitoring data—as here for July—the effectiveness of this buffering can be assessed. It can be seen that the interior absolute humidity follows the exterior surprisingly closely, while the interior temperature varies less, but still more than one would anticipate. Comparing this behavior to the data for December (Fig. 7), it is clear that this "climate permeability" is a result of deliberate ventilation.

7 To demonstrate the role of gas-fired heating on this process, the temperatures and absolute humidities are compared and the scale of the axes adjusted to produce curves of similar amplitude. Each heating cycle results in a corresponding increase in the absolute humidity, clearly indicating the source of the additional water. The contribution of the parishioners can be discounted by examining the curve for Christmas, in which the size and duration of the change relates to heating rather than to the use of the building.

8 Condensation is notoriously difficult to monitor. The most usual way is, as here, to measure surface temperature and calculate dew-point temperature. To stress the relation between the heating of the church and resulting condensation, ambient temperature in this chart is compared to surface and dew-point temperatures. Each probable condensation event is marked with an asterisk and can be traced to heating in the curve above.

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The Treatment of Two Chinese Wall Painting Fragments

Cynthia Luk, Ingrid Neuman, James Martin, Cynthia Kuniej Berry, and Judy Greenfield

Two unrelated Chinese wall painting fragments dating to the Ming dynasty have been the focus of independent study and treatment by two American regional conservation centers.[1] Structural deterioration of rendering layers required intervention to ensure the preservation of both painting fragments. In both cases, treatment decisions were based on technical examination; review of pertinent literature; and consultation with other conservators, conservation scientists, and specialists in Chinese wall paintings. Budgets and deadlines were practical considerations that affected the extent to which technical analysis and treatment could be undertaken. The following presents the construction and condition of these paintings and the rationale behind the materials and methods used for their treatment.

The Female Attendant

In 1992, conservators at the Rocky Mountain Conservation Center treated a Ming dynasty wall painting fragment, *The Female Attendant,* which had been acquired by the Denver Art Museum in 1991. This piece has been attributed to the Shaanxi Province of northern China on the basis of historical and stylistic features.[2] Depicting a female wearing flowing robes and playing pipes (Fig. 1), the fragment was originally part of a larger wall painting in which such attendants may have flanked a central Buddhist figure. The painting's provenance and records of its detachment and restoration are unknown.

Construction

Examination showed that the reverse of the painting fragment was attached to fabric scrim that was adhered with animal glue to a rigid plywood support. The ragged perimeter of the painting fragment was stabilized with plaster (not analyzed) that had been painted a purple-brown color. Paint loss had been inpainted, but not all losses were filled prior to retouching.

Figure 1
The Female Attendant, Ming dynasty, Shaanxi Province, People's Republic of China, 162 × 75 cm, after conservation. The Denver Art Museum.

Technical analysis revealed the presence of two rendering layers composed of dried earth material in a vegetable fiber matrix together with small fragments that appeared to derive from painted or decorated surfaces.[3] A single, white ground layer was observed in cross-section samples. Analysis revealed that the ground was composed of kaolinite and associated minerals. The thinly painted image consists of darkly outlined areas of red, dark green, blue, gray, brown, and ivory paint. Pigments identified in paint samples include red mercuric sulfide, red lead, ultramarine blue, yellow iron oxide, carbon black, calcium carbonate, calcined bone, and possible hematite. Details of the hair ornaments, jewelry, and edges of the costume were sculpted in relief and decorated with gold leaf applied over a fluorescent mordant (not analyzed). Infrared microspectroscopy detected the presence of protein in the ground and vermilion paint samples, possibly present as a binder.

Condition

Major fractures extended through the rendering layers, and smaller cracks were observed in the paint surface, especially along the boundary between the painting and the less flexible plaster surround and fills. By probing the perimeter of the painting, examining two image areas where fills had been removed, and observing the amount of downward movement caused by gently depressing the surface, it was determined that the attachment between the scrim-backed painting and plywood was secure, except for a narrow band along the perimeter of the painting, extending no more than 7 cm from the edge.

The original appearance of the painting had been altered by the removal process, subsequent restoration, and deterioration of original and restoration materials. On later removal of the plaster surround, traces of bright-red and green paint were revealed, which suggested that light exposure, surface oxidation, or other environmental factors also may have contributed to the altered appearance of the painting.[4] The black outlines and some areas of the image had been reinforced by a later hand. Examination with ultraviolet light revealed the presence of a fluorescent surface coating that had been selectively applied, presumably as a consolidant, and that may have caused, or aggravated, paint flaking and loss. Accumulated surface grime obscured the condition of this coating.

Treatment

Structural stabilization of the unstable rendering layers was the primary objective of treatment. The plaster surround and two large interior fills were removed mechanically. A 2.5% (w/v) solution of methylcellulose in water was used to consolidate the exposed edges of the painting. Of the wide range of consolidants tested for consolidation, the methylcellulose solution imparted sufficient cohesion to the layers while causing minimal changes in the visual appearance of the rendering and adjacent ground and paint layers.

A 50% (w/v) solution of Acryloid B-72 in acetone, bulked with an equal volume of glass microspheres,[5] was selected to reestablish adhesion and fill voids between the fabric scrim and plywood support. Of the materials tested, the B-72-microspheres mixture was selected for its adhesive and bulking properties and its ease of reversibility with a heated spatula. The mixture was injected beneath the lifting perimeter of the painting. The edges of the rendering were then coated with an isolating layer of a 5% (w/v) solution of Acryloid B-72 in xylene before losses were filled. The perimeter of the painting was enclosed with Poly Filla bulked with macerated blotting paper and toned with pigment to approximate the color of the rendering layers.

The presence of accumulated surface grime and the discolored, selectively applied surface coating altered the color balance, clarity, and contrast of the image. Cleaning tests for the removal of these materials were conducted using a variety of aqueous and nonaqueous cleaning systems (including solvent gels and chelating agents); however, the friable paint surface was found to be sensitive to mechanical abrasion from dry cleaning methods and aqueous cleaning systems. The uncoated red and green areas were particularly vulnerable to aqueous systems, which were only partially effective in removing accumulated grime. Moreover, the porous structure of the paint resulted in rapid penetration of aqueous and nonaqueous cleaning systems and prevented removal of gel cleaning systems that might otherwise have been used to restrict penetration. Selective removal of grime from coated areas, and subsequent reduction of coatings, was considered but rejected as a treatment option. A sable brush and microvacuum were used to remove standing grime from the surface, but embedded grime and the degraded coating were left intact. Removal of these materials has been postponed until sufficient time and funding is appropriated for a more thorough investigation. The original strip molding was reattached to the edges of the plywood support, and the painting was exhibited horizontally under a Plexiglas vitrine on a temporary basis pending further investigation.

Bearer of Good Wishes

From 1992 to 1995, conservators at the Williamstown Art Conservation Center treated a Chinese wall painting fragment, *Bearer of Good Wishes,* in the collection of the Memorial Art Gallery of the University of Rochester, Rochester, New York. The painting fragment was given to the museum by a private donor, and nothing is known about its provenance. Attributed on stylistic grounds to the late Ming dynasty, the piece depicts a figure standing against a background of clouds (Fig. 2). The figure holds a scepter, known as a *ju-i,* representing a Bearer of Good Wishes, the name by which the painting is now known.

Construction

Following its removal from a wall, the rendering layers were backed with a fabric scrim that was subsequently attached to a rigid support consisting

of cardboard and plywood layers. The perimeter of the painting fragment was secured with plaster, assumed to be plaster of paris but not analyzed. Technical analysis revealed the presence of two rendering layers composed of dried earth materials in a vegetable fiber matrix.[6] The color of the upper rendering layer is gray, and the lower is yellow ochre. Mineralogical analysis showed that the layers are composed of similar minerals: quartz and muscovite mica with lesser amounts of hornblende, biotite mica, alkali feldspar, limestone, iron oxide, calcium particles (salt not determined) occurring in clusters and as individual grains, and trace chlorite. Analysis also revealed the presence of a white ground layer of calcium carbonate and gypsum and subsequently applied preparatory layers containing quartz, calcite, muscovite, lead pigment, and coccolithic calcium carbonate. Particle size analysis indicated that the majority of particles composing the rendering layers were between 1 and 2 μm in diameter. The thinly painted image is dominated by areas of red and green with blue, yellow, orange, black, gray, and cream, outlined in carbon black. Pigments identified in paint samples included lead white, calcium carbonate, yellow iron oxide, carbon black, red mercuric sulfide, smalt, indigo, malachite, and possible hematite. Binder characterization was not performed.

Condition

The desiccated rendering layers were cracked and separating from the rigid support, especially along the boundary between the fragment and the plaster surround. More localized areas of severe cupping of the paint and ground layers also were observed. Later removal of the plaster surround revealed the deteriorated state of the rendering layers (Fig. 3). It was suspected that ambient vibration had caused the rendering layers to powder and that gravity had caused this powdered material to settle to the bottom edge of the painting, leaving voids between the rendering and fabric scrim. This was confirmed by probing the perimeter of the painting and gently depressing the paint surface.

The surface of the painting had been significantly altered by liberal application of fillers and overpaint—a crude enhancement of the black calligraphic drawing so essential to Chinese painting—and the presence of fingerprints in the paint and ground layers, presumably left by a past restorer during a consolidation attempt.

Treatment

The primary treatment objective was physical stabilization of the rendering layers and their attachment to the underlying support. The plaster surround was removed mechanically. Removal of the rigid supports that prevented consolidation from the reverse was considered but rejected as too invasive to the object. Instead, stabilization of the rendering layers by means of grouting was favored (Fig. 4).

A 20% (w/v) solution of polyvinyl butyral (PVB) in equal parts acetone and ethanol, with addition of one part gilder's whiting and one

Figure 2
Bearer of Good Wishes, Ming dynasty, Taoist wall painting fragment, ca. 1600–1650, 201 × 82 cm, prior to conservation. Memorial Art Gallery of the University of Rochester (86.117).

Figure 3
Bearer of Good Wishes (shown in Fig. 2), cross-sectional detail of original rendering layers and added modern support layers prior to conservation.

Figure 4
Bearer of Good Wishes, after conservation.

part glass microspheres[7] (to two parts PVB), provided the desired properties of an adhesive and gap-filling material. In preparation for grouting, loose aggregates were removed from the edges of the painting; and the exposed rendering was consolidated using a syringe application of a 5% (w/v) solution of PVB in equal parts acetone and ethanol.

The grouting mixture was delivered by syringe from the perimeter of the painting while the painting was positioned on edge at an angle of 60–70° from horizontal. Ethanol was first injected into the rendering layers as a wetting agent to encourage the PVB grout to fill the voids. The grout was injected along the elevated edge of the painting, which encouraged inward flow. Viscosity of the grout was adjusted by addition of solvent. The painting was returned to horizontal and weighted for at least twenty-four hours; the operation was then repeated along the opposite side of the painting. Four complete grouting cycles were required to fill the voids, thereby stabilizing the rendering layers. Finally, the edges of the rendering were treated with a PVB filler composed of the 20% stock PVB

grout, small additions of kaolin and fumed silica, and ethanol as needed to form a workable putty.

A variety of consolidants were tested for insecure areas of the matte paint surface. Two consolidants showed satisfactory results. A 5–10% (w/v) solution of Ethulose in water—applied by brush, faced with a Japanese tissue, and weighted overnight—left no discernible tide lines or darkening of the paint surface. Better results were observed using a 5% (w/v) solution of Acryloid B-72 in xylene, applied in a glove-bag enclosure, according to a technique published by Hansen, Lowinger, and Sadoff (1993).[8] In this method, the atmosphere within the enclosure was saturated with xylene vapor for forty-five minutes prior to consolidation. In this xylene-saturated enclosure, a 5% (w/v) solution of Acryloid B-72 in xylene was locally brushed over insecure areas. This process was repeated several times until the paint surface was consolidated. In some areas, curling and lifting paint was brought into plane by application of gentle pressure from a heated spatula over a silicone-release Mylar polyester sheet. Care was taken not to burnish or compress the paint film.

Sensitivity of the paint to mechanical and solvent abrasion precluded the use of many aqueous and nonaqueous systems, gel systems, and chelating agents for removal of accumulated grime and overpaint. Standing dirt and grime were removed with a kneadable eraser called Groom/stick. Additional dirt and grime were removed using a 25% (v/v) solution of water in ethanol (with 2% v/v diacetone alcohol) from the few stable areas of the paint surface using cotton swabs or pads. These areas included the headdress, which contained a thick, well-bound layer of malachite. Otherwise, no attempt was made to remove embedded grime or degraded surface coatings. Selected overpaint and overfills were removed using a 20% (v/v) solution of water in ethanol. Later reinforcement of the black calligraphic lines could not be safely removed but were later muted using thin glazes of retouching.

Retouching was limited and was carried out using Flashe 1300 colors. Exact color matching was avoided; instead, a compatible tone was used that would visually unify the area of damage and would be clearly distinguishable from adjacent, original paint. Losses that exposed white ground were not filled, leaving subsequent inpainting recessed. Losses that exposed the gray rendering layer were not compensated.

Before treatment, the piece had been framed and exhibited as an easel painting; however, this manner of exhibition was reconsidered in favor of exhibiting the work as a fragment of a larger wall painting. To increase rigidity, a maple-wood surround was fitted to the plywood supports.[9] Gaps between the painting and surround were filled with PVB putty, and diluted putty was painted onto the maple over an isolating layer of shellac. The putty was applied in four layers over a period of several days to reduce cracking and shrinkage, then sanded to the level of the maple surround. Multiple layers of neutral-gray latex paint were applied to unify the background, which was recessed from the painting by one-quarter inch (0.635 cm).

Discussion of Both Painting Fragments

Although the Chinese wall painting fragments described here are unrelated by geographical and historical origin or restoration history, each has been visually and structurally altered over time and through human intervention. Surface examination and technical analysis provided an objective basis for evaluation and implementation of treatment materials and procedures. Budgets and deadlines limited the extent to which technical analysis and treatment could be undertaken. Conservators of *The Female Attendant* operated under a low budget with an impending exhibition deadline. By contrast, the budget for technical analysis and treatment of *Bearer of Good Wishes* was significantly higher. Moreover, *Bearer of Good Wishes* was treated over a two-year grant period that was easily extended when it became necessary. In consideration of the fragile condition of these works and the limited resources for research and treatment implementation, treatment of these paintings was restricted to stabilization of the renderings, consolidation of the paint surface, limited removal of grime, and minimal compensation of damage.

Stabilization of the renderings

In the treatment of both paintings, reattachment to the supports and filling of voids were favored over more comprehensive consolidation. Several factors influenced these decisions. First, an overall consolidation of the rendering layers would have required removal of the plywood backings, an approach that was considered too invasive and potentially damaging. Second, generalized application of a consolidant could have penetrated and adversely affected the saturation or reflectance of paint layers. Third, by exhibiting the paintings horizontally or at an incline, the need for more extensive consolidation was avoided.

Selection of the materials and methods used to reattach the rendering layers and fill voids was based on the severity of detachment and testing of a variety of adhesives on test blocks (acrylic and PVA resins, acrylic dispersions, and cellulose ethers). While the rendering layers in *The Female Attendant* were detaching locally along the fragment's perimeter, those in *Bearer of Good Wishes* were detaching more generally and crumbling to fine powder and coarse aggregates. Testing demonstrated that Acryloid B-72 bulked with glass microspheres was an appropriate adhesive filler to remedy the edge delamination observed in *The Female Attendant*. By contrast, polyvinyl butyral bulked with glass microspheres proved an appropriate grouting material for *Bearer of Good Wishes*—the material proved successful on mock-ups and in the treatment of other wall paintings (Hanna, Lee, and Foster 1988). Further, the high molecular weight of the polymer decreases penetration into the rendering layers.

Consolidation of paint surface

Considerations in the selection of consolidants for the paint surface of each painting included adhesive strength, workability, aging properties, and effect on surface appearance after drying. Subtle differences in the

quality and condition of the paint surfaces accounted for the different choice of materials and methods of application. Methylcellulose provided sufficient adhesive strength without altering the reflectance or saturation of the paint surface on *The Female Attendant.* Equal success was achieved on *Bearer of Good Wishes* using Acryloid B-72 in xylene, applied in a glove-bag enclosure saturated with xylene vapor.

Removal of grime, coatings, and restoration

The friable, porous, water-sensitive condition of the paint surface prevented safe and uniform removal of embedded grime, coatings, and restoration. Aqueous and nonaqueous solvent systems could not be used safely on either painting, except in a few locations on *Bearer of Good Wishes.* The porosity of both paint surfaces prevented adequate clearance of gelled or thickened cleaning systems. Porosity and the underbound structure of the paint on each piece raised questions concerning the use of chelating agents, which might have resulted in removal of certain pigments. Soft brushes and a microvacuum were used to remove standing grime from the surface of *The Female Attendant,* while use of a Groom/stick kneadable eraser was permitted on *Bearer of Good Wishes.*

Another important consideration in cleaning was an uncertain knowledge of how the surface had altered, how the painting might have originally appeared, and how the paintings would be further altered through cleaning. Lacking sufficient resources for further investigation of the chemical composition of the surface layers, removal of coatings, overpaint, and embedded grime from *The Female Attendant* was not attempted; the rationale for this decision is aptly underscored by Mora, Mora, and Philippot (1984): "The removal by cleaning of all non-original materials does not restore the work to its original state, i.e. the state in which it was left by the artist on completing the original work. It simply reveals the present state of the original materials."

Under the guidance of the curator, selected overpaints were removed from *Bearer of Good Wishes.* These sites were selected based on the likelihood that original design elements obscured by the overpaint might be recovered. In the course of treatment, overpaint removal did reveal greater complexity in the cloud formations and slight differences in some decorative elements.

Compensation

The extent and degree of compensation performed was determined by the visual condition of the paintings and discussion between conservators and curators. Given that coatings and restoration were not removed from *The Female Attendant,* retouching of the image was not considered an appropriate option. Compensation was restricted to application of a Poly Filla surround and fills that were toned with raw sienna and red ochre dry pigments blended to match the color of the exposed rendering layer.

By contrast, previous restoration had compromised the visual intention and subtlety of *Bearer of Good Wishes* to such a degree that more

extensive compensation was proscribed by the curator. Paint losses revealing white ground were toned with a neutral color that approximated but did not match the adjacent color fields. Paint and ground loss that exposed the rendering were not compensated. The crudest reinforcement of black outline that could not be removed safely was muted with thin glazes. Flashe 1300 colors, a type of vinyl emulsion-based paint, was selected for retouching because of its matte appearance on drying and its synthetic composition.

Rehousing

Choices of rehousing reflected exhibition needs, tempered by conservators' recommendations and cautions. *The Female Attendant* was temporarily exhibited at the Denver Art Museum as a work under investigation, reframed with wooden edge molding, and presented horizontally under a Plexiglas vitrine. The wooden frame for *Bearer of Good Wishes* at the Memorial Art Gallery was not reused; rather, a neutral, recessed surround was fashioned, and the painting was exhibited approximately 10° from vertical. The painting was installed in the museum's permanent Asian collection.

Acknowledgments

The authors wish to acknowledge the assistance of numerous colleagues who contributed to the examination, technical analysis, and treatment of the paintings: Candace Adelson, Richard Brown, Thomas Hopen, Pam Martoglio, Chris Stavroudis, Richard Wolbers, and Williams College for use of the Cambridge Stereoscan scanning electron microscope. For assistance in preparing this text for publication, the authors thank Beth Greenfield Tulipan.

Notes

1 Examination and treatment of the Denver painting was undertaken by Cynthia Kuniej Berry and Judy Greenfield at the Rocky Mountain Conservation Center. Examination and treatment of the Rochester painting was undertaken by Cynthia Luk and Ingrid Neuman at the Williamstown Art Conservation Center. Technical analysis was performed by James Martin at the Williamstown Art Conservation Center, except as noted.

2 Attribution was made by Julia White, associate curator of Asian arts, Denver Art Museum.

3 Technical analysis involved examination of layered and particle samples using reflected visible light microscopy, polarized light microscopy, fluorescence microscopy, and scanning electron microscopy with energy-dispersive X-ray spectrometry. Infrared microspectroscopy was provided by Pam Martoglio at Spectra-Tech, Inc., Shelton, Conn.

4 The possibility that some surface discoloration or darkening may have resulted from chemical alteration of pigment, especially vermilion or lead-based pigments, was considered. Definitive analysis to identify such alteration products was precluded by time constraints and was a factor in the decision not to clean the painting.

5 The glass microspheres used were soda-lime borosilicate glass manufactured by 3M Specialty Additives.

6 Technical analysis involved examination of layered and particle samples using reflected visible light microscopy, polarized light microscopy, fluorescence microscopy, and scanning electron microscopy with energy-dispersive X-ray spectrometry. Mineralogical analysis was provided

by Thomas Hopen and Richard Brown of MVA, Inc., Norcross, Ga., using polarized light microscopy, scanning electron microscopy with energy-dispersive X-ray spectrometry, and analytical electron microscopy.

7 The glass microspheres used were Scotchlite Glass Bubbles.

8 The technique involves the application of a stable thermoplastic resin solution in a chamber saturated with the solvent in which the resin is dissolved. Acryloid B-72 and polyvinyl acetate have been used successfully under such conditions. Hansen's method differs from past uses of solvent-saturated environments in that the object is placed in the chamber *prior to,* rather than *after,* the application of solvents. This induces further penetration of the resin solution without increasing solution viscosity at the surface, thus encouraging efficient wetting of the pigment particles and even distribution of the resin solution.

9 A supporting maple-wood frame was constructed by Hugh Glover, conservator of furniture and wooden objects, Williamstown Art Conservation Center, and was installed around the existing plywood backing of the wall painting. The design and materials described here were chosen for their strength and easy reversibility. The frame was sized to snugly fit the plywood backing and to sit below the surface of the wall painting. Four maple battens were screwed into the back to trap the plywood backing. Screws were also used to fasten the battens to the maple frame as well as the plywood backing. The areas of the spandrels were filled with plywood. Three lengths of 1-inch (2.64 cm) aluminum channel were screwed to the plywood backing within the recess created by the new framing.

Materials and Suppliers

Acryloid B-72 is a copolymer of ethylmethacrylate/methacrylate (70/30) produced by Rohm and Haas, Philadelphia, PA. Acryloid B-72 is also known as Paraloid B-72.

Ethulose is a water-soluble cellulose ether composed of ethyl hydroxyethylcellulose. The ethulose used was obtained from Conservation Materials, Ltd., Sparks, NV 89431.

Flashe® 1300 colors are water-soluble matte colors manufactured by Lefranc and Bourgeois, LeMans, France, using a vinyl emulsion binder.

Groom/stick is described by the manufacturer (Picreator Enterprises Ltd., London) as a processed, kneadable, natural rubber that is free of moisture, solvents, and chemical additives.

Methylcellulose is a water-soluble cellulose ether. The material used was obtained from Gaylord Brothers, Syracuse, NY.

Poly Filla is a synthetic compound of calcium sulfate with cellulose filler manufactured by LePage Ltd., Bremalia, Ontario, Canada.

Polyvinyl butyral is a polyvinyl acetal. The PVB used is marketed as Mowital B60H, and is available from Hoechst, Charlotte, NC.

Scotchlite Glass Bubbles, 3M Corp., St. Paul, MN.

Soda-lime borosilicate glass manufactured by 3M Specialty Additives, St. Paul, MN.

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Paintings on Silk and Paper from Dunhuang at the British Museum

Conservation Methods

Lore Erwine Fleming

THE PAINTINGS and sketches from Dunhuang are among the most important treasures of the British Museum. The paintings, along with other items, were discovered by a Taoist monk around 1900 in a sealed repository next to Cave 17 at Dunhuang (see map, page xiii). Mark Aurel Stein (later Sir Aurel Stein), the British archaeologist, explorer, and orientalist, visited Dunhuang in 1907, having heard of the existence of a great library (Stein 1987; Hopkirk 1985). After some delays, he obtained several thousand items from the repository, which were then sent to England and India. India received three-fifths of the items and England two-fifths—the proportions reflecting their relative levels of sponsorship for Stein's journey. The British Museum's share included prints on paper, paintings, drawings, and sketches on paper (Fig. 1), scrolls of stencils, banners, booklets, paper flowers (Fig. 2), a paper valance, and, of course, paintings on silk (Fig. 3).

The paintings on paper and silk in the museum's collection date from the eighth to the tenth century C.E. (Whitfield and Farrer 1990), and

Figure 1
Sketch of camel, detail. 30.5 × 84.5 cm (British Museum 1919-1-1-077).

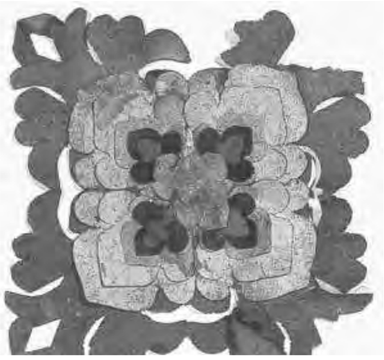

Figure 2
Paper flower. 16 cm diameter (British Museum 1919-1-1-0230).

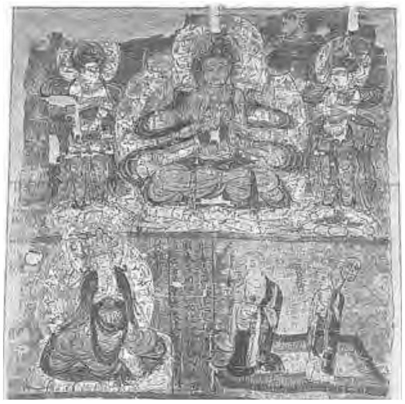

Figure 3
Banner, *Avalokitésvara with Suryagarbha Candragarbha and Maitreya Bodhisattvas.* 61 × 58 cm (British Museum 1919-1-1-059).

their condition varies from small fragments to almost complete works of art. Many of the temple banners and Paradise paintings in relatively good condition were repaired in antiquity by the technique of affixing strips of paper manuscripts to the backs and resewing the silks. In contrast, many of the paintings on silk were in poor condition, being mere crumpled bundles of fragments. Tasks required for their modern conservation were flattening of the fragments, assembly of the fragments into more complete images, and consolidation of the assembled images into a suitable format for storage and display.

Conservation of Works on Paper

Damage to the works of art on paper from Dunhuang has been caused by handling, insects, or dampness through the years. Because of these degradations, many paintings now consist of fragments, which can sometimes be consolidated and mounted to compose one image again. The paper carrying the image is usually quite robust; in these cases the holes and lacunae are filled with matching paper, often supported from the verso with a lighter paper, which is 3 mm larger than the missing area and attached with paste to the back of the original behind the repair.

The paper preferred for these repairs is a fairly heavy, long-fibered mulberry paper, handmade in Japan (Barrett 1983; Hughes 1978), which matches the characteristics of the old Chinese paper. (It has not been possible to match these characteristics with a modern Chinese paper.) The fine paper used on the verso may be a handmade *tengujo,*[1] or something slightly heavier if the original is very fragile. These strong, flexible, and transparent Japanese papers are attached with gluten-free wheat starch paste.[2] The repair is toned to a matching background color with watercolors.

Sometimes the damage is more extensive, and the whole object is in very poor condition (Fig. 4). The verso of *The Arhat Kalika as Monk* shows problems caused by some old linings and repairs, probably made while the artwork was in use in Dunhuang—although these interventions no doubt saved the painting from disintegration. When all the old repairs were removed, the piece was very fragile and required extensive repairs and a new lining. These repairs were achieved with the Japanese technique

Figure 4
Verso of *The Arhat Kalika as Monk,* showing the poor condition of the painting. 43.5 × 26 cm (British Museum 1919-1-1-0169*).

of relaxing the painting with water, brushing it flat, and applying pasted lining paper. The weight and fragility of the original determine the choice of lining paper (Koyano 1979). In this case it was fairly heavy.

The design of the image is never restored. In the British Museum, the ethic of conservation calls for the repair to be clearly visible to scholars without being too intrusive to viewers when the object is on exhibition (Fig. 5).

Pigments employed by the original artist sometimes cause problems for the conservator. For example, the green pigment verdigris (basic copper acetate) can hydrolyze, becoming acidic and "burning" holes in paper (Fig. 6). The new supporting paper on the verso is placed behind any remaining verdigris to hold the area and prevent further loss, and the lacunae are filled in as before and left a neutral tone. The area of verdigris is also deacidified by localized brushing with magnesium bicarbonate in a solution of Klucel G (hydroxypropylcellulose) as recommended by Banik, Stachelberger, and Wächter (1982). The magnesium bicarbonate stops the attack of the copper acetate on the paper by neutralizing free acid, and the cellulose encapsulates the pigment grains, separating them from the paper fibers and preventing the access of moisture that leads to hydrolysis.

Problems can also arise when lead-containing pigments have been used, such as white lead carbonate and a red oxide of lead (Pb_3O_4), as they blacken in the course of time by reaction with hydrogen sulfide from the atmosphere (Fig. 7). This blackening is treated with a local application of hydrogen peroxide in diethyl ether, which oxidizes the exposed surface layer of the blackened pigment to white lead sulfate (Daniels and Thickett 1992).

Figure 5
Dharmatrata, showing repairs. 41 × 29.8 cm (British Museum 1919-1-1-0168*).

Figure 6
Talisman of the Pole Star, showing loss of paper caused by degradation from verdigris pigment. 42.7 × 29.7 cm (British Museum 1919-1-1-0170).

Figure 7
Avalokitésvara, showing blackened red lead pigment. 49.8 × 29 cm (British Museum 1919-1-1-0159).

Stains are the most difficult to treat. They could have been caused by lamp oil, candle wax, food, or dirt. Washing often puts the image at risk, and there is no guarantee that these stains will respond. Some prints were washed and yet are still stained, so it is sometimes better to accept the stains as part of the history of the work of art.

Conservation of Works on Silk

Many of the paintings on silk consisted of bundles of crumpled fragments that had fortunately been stored in solander boxes since their arrival at the British Museum in 1908 (Fig. 8) (Whitfield 1982–85). The late Alfred Crowley, a conservator in the Department of Conservation from 1967 to 1990, spent several years treating fragments by floating them on a pool of water on glass to relax and flatten them, and then drying them between sheets of blotting paper. The colors were absolutely fast and totally unfaded. The other astonishing fact was that although these paintings on silk were fragmentary, each small piece of silk was strong enough to be handled. Some fragments had been stuck onto paper in the past—possibly by a desperate British Museum conservator shortly after 1908. This very crude method of conservation no doubt prevented the loss of many of the small pieces of silk.

Figure 8
Bundles of silk fragments before conservation.

When the design of the fragments could be seen, it was possible to assemble them into larger pieces with curatorial help. Even with gaps in a painting, it was possible to visualize most of the image. Conservation consisted of toning a long-fibered Japanese mulberry paper to a suitable background color with organic pigments such as *yasha*[3] and lining the fragments that belonged together, after they were carefully positioned in relation to one another and moistened face down on a facing paper.

They are lined using a technique that hinges the lining into its correct position on the workbench in relation to the fragments before pasting. The silks are placed in their correct position on a rayon facing paper, and the lining is positioned dry. One centimeter of the lining edge is pasted to the bench to act as a hinge. The lining paper is then turned back and pasted, turned onto the verso of the fragments, and brushed down. For larger paintings, it is sometimes a four-handed job to place the lining in the correct position without disturbing the fragments.

The adhesive used is a 1:1 mixture of ten-year-old wheat starch paste and fresh paste (Winter 1984; Wills 1984). Aging paste is stored in a cellar in large ceramic pots, and one potful is made every year (Fig. 9). The mixed paste is much softer than fresh paste, with greater flexibility. Gluten-free wheat starch is always used.

For one painting, the borders were in relatively good condition so that the size of the original was known (Fig. 10). Several very large pieces of the painting were found, but there were still very large gaps. Because of the size of this painting (208.5 × 202.5 cm), Crowley had to build a bridge of wooden planks, positioned a few centimeters above the painting, which he moved along so that he had access to each area during the lining process. After the lining had dried, the whole painting was slightly moist-

Figure 9
Cellar with jars of aging paste. One jar is made per year.

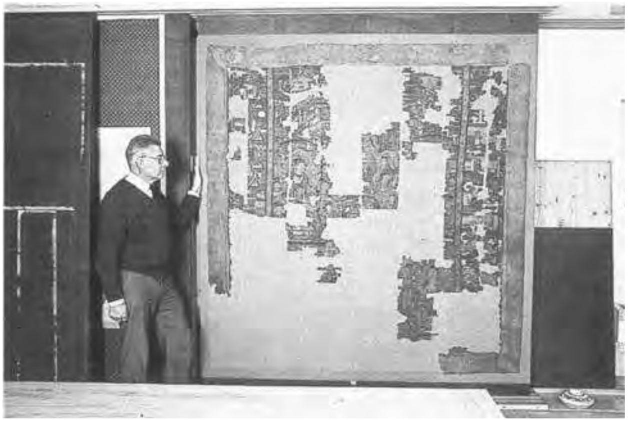

Figure 10
Conservator Alfred Crowley with a large painting consisting of fragments. 208.5 × 202.5 cm.

ened and placed on a drying board for several months (Webber and Huxtable 1985). During this period more fragments were found; it was then possible to place these in their correct positions from the front.

Mounting

Small paintings and sketches on paper are inlaid in European paper of a suitable weight made to British Museum specifications.[4] One method is to pare the inner edge of the inlay and overlap about 3 mm over the edge of the verso of the original or its lining. Another method is to cut the inlay aperture 1 mm larger than the original and attach the painting with 3 mm wide strips of Japanese paper. The aperture of the mount can then show the whole object safely without danger of damage to the edge (Fig. 11). The corners of the mount are rounded, the sides are sanded, and the board is thick enough to hold an adjacent mount away from the surface of the painting while in storage in a solander box. The mounting board is acid free and also made to British Museum specifications. An interleaving tissue is placed in each mount during storage. The small silk paintings are mounted in exactly the same way as the small paintings and sketches on paper.

Larger paintings on silk are mounted on panels made either in a similar manner to drying boards or made of Tycore.[5] The decision as to which panel to use depends upon the size of the paintings, the smaller ones usually going onto Tycore. The wooden trellis is made with "woven" joints so that the trellis does not warp (Webber and Huxtable 1985). The wood used for the core has to be resin free and straight grained, without knots; it cannot be a wood that will stain paper when wet or cause the paper to become acidic. *Liriodendron tulipifera* has been found to have these characteristics. Before the painting is attached, the core is covered with eight layers of paper—a process that creates air pockets (Koyano 1979).

The verso of *Buddha with Cintamani-cakra and Vajragarbha* has a floral decoration that was obviously intended to be shown through a

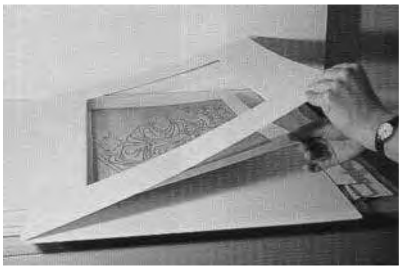

Figure 11
Mount with inlaid sketch.

Figure 12
Verso of *Buddha with Cintamani-cakra and Vajragarbha,* showing floral decoration behind wooden trellis. 81.8 × 74.7 cm (British Museum 1919-1-1-071).

trellis. Because the flowers were not evenly spaced, each window had to be carefully measured for the trellis to re-create the original effect (Fig. 12). The painting and the trellis are held unglazed in a frame.

The work of sorting the fragments is ongoing; the museum expects to bring the whole collection into good condition over the next few years.

Acknowledgments

The author would like to thank Andrew Oddy, Keeper of the Department of Conservation at the British Museum, for his assistance in editing this paper.

Notes

1 *Tengujo* is made from the finest long kozo fibers. It is silky and very fine—sometimes only 0.03 mm thick—but strong, porous, and flexible (Hughes 1978).

2 Gluten is the protein content of wheat starch; it is a hard and brittle solid when isolated and dry. Because the adhesive for conservation should remain flexible, it is important to exclude gluten.

3 The water from boiling alder cones.

4 Paper from cotton or rag fiber, with neutral pH and low hygroexpansivity, both across the grain and with it.

5 Tycore is a panel of rigid, acid-free board with a honeycomb center. It is 15 mm thick and can be framed if desired.

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Conservation Treatment of Two Ming Dynasty Temple Wall Paintings

Eric Gordon

THE BIRMINGHAM MUSEUM OF ART in Birmingham, Alabama, has in its collection two Buddhist temple wall paintings (Figs. 1, 2) from the Ming dynasty. Based on their iconography, these paintings were titled *The Pure Land of Amitabha* and dated roughly to the fifteenth century. In many ways, these mural pieces are distinctive; yet in construction, style, and composition, they show characteristics found in many other temple wall paintings. This article discusses the recent conservation of the murals, which combined traditional and modern treatment methods.

The Birmingham paintings are thought to be the two outside panels of what must have been a much larger composition. It is not known where the paintings originated. In style, they are closest to paintings from Fahaisi in the Beijing area. No inscriptions or graffiti are present, and the quality of the work is high, which suggests that the murals are from an important temple in a major city.

Figure 1
The Pure Land of Amitabha, fifteenth century. Gilding, paint, and gesso on plaster, 3.20 × 1.61 m. Right panel, after treatment. Birmingham Museum of Art (1987.34).

Figure 2
The Pure Land of Amitabha, 3.20 × 1.61 m. Left panel, after treatment. Birmingham Museum of Art (1987.34).

The two paintings form an architectural unit: a complete interior wall. Each panel is approximately 3.20 × 1.61 × 0.14 m and weighs nearly one metric ton (10^3 kg). Because of their great weight and size, the panels were not removed from their crates after shipment to the conservation studio. After the lid of the crates was removed, exposing the elaborately painted front surfaces, the murals were examined, tested, and treated on the painted side only.

One of the most distinctive features of these paintings is that they were not cut into small blocks to facilitate removal from their original locations and transport to the West. Most likely because of their fairly compact size, the paintings were moved as a whole from their original temple location, and the backings were kept intact.

Technique

The Pure Land of Amitabha mural has a complex structure (Fig. 3). It appears that a heavy wooden, inner framework runs the length and width of the mural in a large grid. This latticework is covered with a plasterlike material containing long, hemplike fibers that run throughout the plaster. The plaster is then covered with a fairly coarse, long-fibered hemp or strawlike material. This layer is loosely adhered with plaster; however, it is distinct from the plaster beneath it. On top of this hemplike layer is a fine but loosely woven, off-white fabric. This fabric provides reinforcing for the finer plaster support. The plaster or light-colored clay on top of this fabric is off-white or slightly gray, and it is finer in composition than the underlying plaster wall. The finer clay or plaster contains short-fibered hemp and finer silica particles. In cross section, one can see numerous, very thin layers of increasingly finer clay built up to the paint layer.

In general, the paint layer is very thin and has a transparent quality. Black outlines are blocked in with various colors. On close inspection,

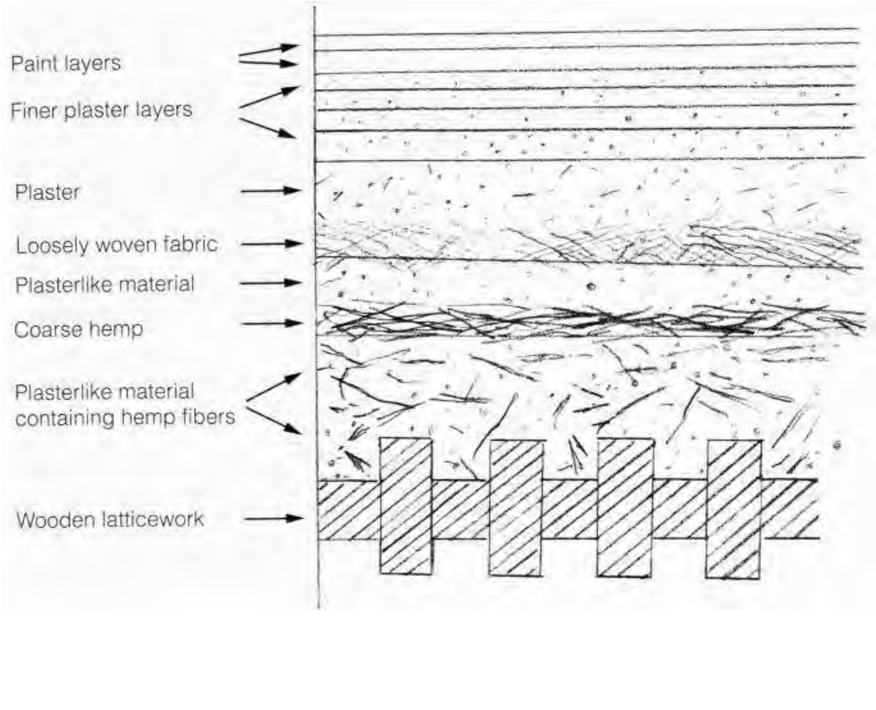

Figure 3
Schematic diagram of wall painting structure.

one can see an underdrawing in different colors in some areas. The paint appears to have been applied in washes of various opacities. Blacks and dark greens are more opaque and were applied in layers. The greens, most likely malachite, were not ground as finely in order to maintain their rich color. Pigments were not analytically identified; however, the palette is similar to the other Chinese wall paintings, such as those at the Royal Ontario Museum that were examined at the Canadian Conservation Institute and described by Gordon and Phillimore (1984).

Another distinctive feature of these paintings is the raised, gold gesso ornamentation that lends a jewel-like, delicate appearance to the dark palette (Fig. 4). From cross sections, it appears that a fairly thick, gluelike material was applied to the sculpted plasterwork before the gold was applied. This application helped preserve the gold, making it harder and more impervious to water seepage and damage.

Condition

The mural structure was of generally good condition and showed no serious damage (Fig. 5). The wooden framework and underlying plaster and hemp layers were in stable condition, although the loosely woven fabric layer had detached from the plaster wall and hemp in numerous areas, resulting in many scattered air pockets. There were three or four large cracks extending half the length of each painting from the bottom edge to the middle of each mural; however, there appeared to be no sign of loss of the support. The entire surface exhibited pronounced cupping with a large network crackle pattern. Underneath these cupped areas, the fabric was detaching from the plaster substrata.

Many small, scattered areas of loss in the plaster support were seen, primarily in the bottom third. The paint layer exhibited extensive flaking and losses, also in the bottom third, as well as in the blacks and

Figure 4
Right panel, detail, during cleaning.

Figure 5
Left and right panels, before treatment.

coarsely ground greens. This was most noticeable in the depiction of the so-called Wish-Granting Trees, where paint was not only lost but dissolved, displaced, and reformed into discrete pigment agglomerates in the lower areas of the painting. Water damage may have destroyed the cloud-like designs and the bottom 7–8 cm of the murals. These areas were quite faint and abraded.

Evidence of one minor early restoration treatment was found. In an attempt to consolidate flaking paint at some time in the past, a thin resin had been clumsily applied to some areas of cleavage toward the bottom of the paintings and around the platform of the Buddha in each one.

A thick layer of soot and surface grime covered both paintings. Because the paintings were porous and unprotected, dirt had penetrated the plaster due to water seepage and had stained and disfigured the paint layer, obscuring the images.

Treatment

Because of the conditions described here, the paintings were not considered exhibitable or stable. The basic plan of treatment was to remove the soot and surface grime, as safety permitted, stabilize the cracks, readhere the support layers and flaking paint, set down the cupping, and reintegrate the paint layer to unify the pictorial image. The paintings were treated in a horizontal position; because the panels are relatively narrow, areas in the center could be reached.

As more extensive tests were performed, many other problems soon became apparent. The first of these was cleaning. Tests using dilute solutions, then progressively more concentrated ones were carried out with organic solvents and alcohols, mild soaps and detergents, and mixtures of ammonium and sodium bicarbonate with additives. None of these methods—which are typically used to clean paintings, including wall paintings—worked on these murals. The paint layer was soluble in water, and

solvents seeped into the surface and did not remove the dirt or soot. The gold had a harder, more impervious surface and could be cleaned with saliva; however, saliva also solubilized the paint. Ideally, what was needed to clean the murals was a soap that could break through the soot, dissolved in a solvent that would not affect the paint layer.

With the help of Richard Wolbers from the Winterthur Conservation Program at the University of Delaware, a solvent-soap-gel system was developed to cut through the soot and grime without disturbing the paint. This solvent-based, detergent gel consisted of xylene (200 ml), benzyl alcohol (50 ml), Armeen CD (15 ml), Carbopol (2 g), and Triton-X (20 g). The gel was diluted further, after experimentation, with a small amount of Shellsol (a mixture of hydrocarbons). The solution was applied with a cotton swab and rinsed thoroughly with Shellsol. The paint layer was not affected, and the dirt and soot were partially removed (Fig. 4). The purpose of this step was not to remove all the grime covering the paint but to bring back a truer sense of the color relationships. This method solved the problem of grime and soot removal. Since this treatment, however, it has been noted that, in certain cases involving oil paintings, Triton-X can be difficult to remove completely during rinsing. No residuals were found on the murals in this case. Should this cleaning solution be used again, however, one might try eliminating the Triton-X and rinsing with xylene, which has a higher aromatic content than Shellsol.

Another cleaning step involved removing accretions and displaced paint. Water damage had caused some displacement of paint through the centuries. These flakes could not be saved or satisfactorily matched up to their original sites. Therefore, along with accretions, they were mechanically removed with a scalpel.

Actively flaking paint and gold areas that had not yet been cleaned because of their unstable condition were reattached with a synthetic adhesive applied with a small brush. Ethyl alcohol was first applied to an insecure area with a small brush or through a syringe, followed by a dilute solution of the synthetic adhesive Beva D-8 in water. Beva D-8 was chosen because it could sufficiently soften the paint and support layer but not dissolve it. Also, this solution allowed sufficient time for the adhesive to dry; so the area could be manipulated, if necessary—a feature that became useful in later steps. Any excess adhesive could be removed with acetone. Once the flaking areas were stabilized, they too were cleaned.

After the paintings were cleaned and the actively flaking paint reattached, consolidation treatment began on lacunae, branched areas of cleavage, and cracks. The same adhesive used to set down the flaking paint was used for these areas but in different concentrations. Whereas a very dilute solution had been brushed into the actively flaking areas, a thick, concentrated solution was injected into the interlayer cleavage.

To treat lacunae and large, branched areas of cleavage, ethyl alcohol was first injected through a syringe into an opening or crack, which served to open up the connecting network of cleavage and allow the adhesive to flow with greater ease. When the alcohol had completely evaporated, Beva D-8 was injected into the loss, filling the empty spaces and

opening channels beneath the paint layer. After the consolidant had settled and started to set, silicone-release Mylar was placed over the area and cleavage was set down with a warm tacking iron (Figs. 6, 7). This greatly reduced the cupping. To ensure the adhesion of the layers and hasten the drying of the adhesive, a Thermofilm heat blanket and conformable weights (fine lead shot contained in fabric) were placed on top of the consolidated area. The heat blanket was controlled by a rheostat and set at a low heat.

Small areas of cleavage and cracks were treated in a similar manner, usually with a tacking iron and without the heat blanket. Small lacunae that appeared secure and had no prominent cracks or openings were not treated. This method of consolidation worked well on the paintings. Flaking and interlayer cleavage were stabilized, and cupping was greatly reduced.

At this stage, a 5% solution of Acryloid B-72 in xylene was brushed over the surface to further consolidate and harden the paint layer and saturate the slightly stained, water-damaged areas. Because the concentration was low, the B-72 did not change the texture, matte appearance, or any other aspect of the surface.

Discussion

Approaches to filling and inpainting of wall paintings are varied. Whether one should leave a mural with natural and human damage left exposed, or restore losses to hide damage, is a subjective question. There are as many approaches to this question as there are wall paintings; which is as it should be, as the artwork itself should be the determining factor in deciding an approach. In the case of the Birmingham paintings, most of the paint losses were contained in specific, key areas, where loss of paint color contrasted greatly with the exposed clay, as in the areas depicting the Wish-Granting Trees. If left exposed, such losses would detract from the overall aesthetic unity of the murals. Therefore, the curator and

Figure 6
Right panel, detail, raking light, before treatment.

Figure 7
Right panel, detail, raking light, after setting down cleavage.

Figure 8
Left panel, detail, before inpainting.

Figure 9
Left panel detail, after inpainting.

conservator decided that the numerous losses should be toned to match the surrounding area, so a viewer looking at the mural from a standard distance would not be distracted by the exposed white clay. Only the most disruptive, deep losses in the clay support were filled with a pigmented, animal-skin glue and gesso putty with added polyvinyl acetate emulsion. Most of the cracks were left unfilled.

Inpainting was carried out in a synthetic medium with preground, tubed Lefranc and Bourgeois Restorer's Colors. Watercolors were eliminated as an option because if a decision were made to alter the retouching in the future, it would be difficult to remove without affecting—perhaps even dissolving—the original, water-sensitive paint layer. Lefranc and Bourgeois colors can be removed with very dilute solvents, such as mineral spirits containing low aromatic hydrocarbons, without affecting the original paint (Figs. 8, 9).

Conclusion

Treatment of the two Ming dynasty murals at the Birmingham Museum of Art stabilized their condition and returned them to a more cohesive, tonally correct image. Materials used were reversible whenever possible, and applications of resins and adhesives were kept to a minimum.

Acknowledgments

The author would like to thank Donald Wood, curator of Asian Art at the Birmingham Museum of Art, for his knowledge and support in this project.

Materials and Suppliers

Acetone AR, Conservation Materials Ltd., 1165 Marietta Way, P.O. Box 2884, Sparks, NV 89431.

Acryloid B-72, Conservation Materials Ltd. (manufactured by Rohm and Haas Company, Philadelphia, PA).

Armeen CD, cocamine, Akzo Chemicals Inc., 300-T South Riverside Plaza, Chicago, IL 60606-6613.

Benzyl alcohol, Fisher Scientific, 1 Reagent Lane, Fairlawn, NJ 07410.

Beva D-8, Conservation Materials Ltd.

Carbopol 954, B. F. Goodrich Co. Chemical Group, 9911-T Brecksville Road, Cleveland, OH 44141.

Ethyl alcohol, Conservation Materials Ltd.

Lefranc and Bourgeois Restorer's Colors, Conservation Materials Ltd.

Shellsol, Odorless Mineral Spirits, Petroleum Naphtha NOIBN, Inland Leidy, 2225 Evergreen, Baltimore, MD 21216

Thermofilm heat blanket is a carbon-coated fiberglass enclosed in heavy Mylar. No wire elements run through it, and the amount of heat can be regulated by a rheostat. It is available from Canada Thermofilm Ltd., 8421 Keele St., P.O. Box 720, Concord, Ontario L4K 1C7, Canada.

Triton-X 100, Fisher Scientific.

Xylenes AR, Conservation Materials Ltd.

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Research on Protection of Ancient Floor Tiles in the Mogao Grottoes

Gao Nianzu, Jia Ruiguang, and Wang Jinyu

Located in the Mogao grottoes at Dunhuang are a wide variety of floor tiles made during medieval times in China. The floors of nearly fifty caves are lined with more than twenty thousand tiles of at least twenty different designs and patterns. These tiles were produced over the centuries, from the Northern dynasties (420–589 C.E.) to the Yuan dynasty (1271–1368 C.E.). The tiles made since the Tang dynasty (618–906 C.E.) are of the best quality. A great variety of tiles were manufactured during the Five dynasties period and during the Song and Western Xia dynasties. Taken together, these ancient floor tiles are an important component of Mogao grotto art.

In 1978, research on the protection of the floor tiles began. Abrasion damage, mainly caused by foot traffic, was identified as a problem. Because of the desire to maintain the design integrity of the ancient floor and to avoid intrusive visual elements, an overlaid walkway or other physical protection methods were not considered. Instead, various consolidants were tested as protective coatings. Results from two stages of experiments suggested that polyurethane coating and infiltration with traditional tung oil can increase the wear resistance of the tiles (Gao, Jia, and Wang 1993).

Selection of Consolidants as Coating Materials

A consolidant that is to be used as protective material for floor tiles should be transparent, of suitable viscosity to penetrate the tiles, and sufficiently abrasion resistant to provide a durable coating. Two kinds of coatings were selected for testing: synthetic resins and raw tung oil.

Synthetic resins: Polyurethane resin was selected for its elasticity, durability, and wear resistance. For comparison, epoxy resin coating was also tested.[1]

Raw tung oil: This pale yellow oil extracted from the seeds of tung trees is quick drying and provides a strong, nonsticky coating. It has a density of 0.924–0.925 g cm^{-3} and a melting point of 2–3 °C. Tiles permeated with raw tung oil are resistant to erosion by water and alkali, and to deteri-

oration by light and the atmosphere. The "golden tile" used in many important ancient Chinese buildings was made by permeating tiles, after firing, with raw tung oil.

Preparation of Samples and Testing of Consolidants

The equipment used to test the floor tiles were a road-abrasion testing machine, a high-pressure sandblasting machine, and a freeze-thaw testing machine.

Most of the testing samples were taken from the Meridian Gate of the Beijing Palace Museum during a renovation project. Fired during the Ming dynasty, these tiles are strong, dense, and homogeneous, as demonstrated by the consistency of the testing results. For comparison, the samples were treated with different consolidants in wear-resistance and freeze-thaw tests. Some tile samples taken from the Mogao grottoes were also treated and tested. These tiles were produced during the Tang and Song dynasties.

In preparation for testing, the sample tiles were precisely cut into 15 × 15 × 4 cm square pieces with perpendicular sides and flat surfaces to ensure good contact with the steel balls of the road-abrasion testing machine. The test pieces were oven dried to facilitate penetration of the consolidant and weighed before the consolidant was applied. Results are shown in Table 1 for the fifteen samples tested.

Tests of polyurethane varnishes on Meridian Gate tiles

In the first part of the experiment (Table 1, samples 1–8), eight Meridian Gate tile samples were tested, each with a different polyurethane varnish. Fifty grams of consolidant with 42% solid content were applied to one side of each tile. The other sides were left untreated for comparison. The consolidants used in samples 1 and 2 were too viscous to penetrate the tiles. In samples 3–8, all the consolidants permeated the tiles and produced a dark, homogeneous, dull, nonreflective surface. Penetration of 1–2 mm was observed when cross sections of these samples were examined under ultraviolet radiation after treatment with aqueous sodium fluorescein. Abrasion tests were performed several days (usually more than fourteen) after the application of the consolidants.

Tests of raw tung oil on Meridian Gate tiles

In the second part of the test, raw tung oil was applied to tile samples 9 and 10. Following the Chinese traditional methods of manufacturing "golden tiles," both coating and soaking techniques were tested. Abrasion resistance tests were performed after one year of hardening.

Coating method (sample 9): To facilitate the penetrability of raw tung oil, 20 parts of kerosene (by volume) were added to each 100 parts of oil. Fifty grams of the oil-kerosene mixture was applied to the surface of each tile.

Table 1 Results of abrasion-resistance test results

			Abrasion machine		Sandblasting		
Tile sample number	Consolidant	Surface condition	Abrasion (g)	Wear resistance[a]	Abrasion (cm^3)	Wear resistance[a]	Appearance after coating
1	Polyurethane floor paint	coated	0				Partially reflective
		uncoated					
2	Polyurethane floor varnish	coated	trace				Partially reflective
		uncoated	trace				
3	Wet-fixation varnish (WFV)	coated	3.2				Darker, dull, nonreflective
		uncoated	63.2	19.8			
4	WFV + epoxy resin	coated	3.3				Darker, dull, nonreflective
		uncoated	77.7	23.5			
5	Forbidden City floor varnish	coated	1.0				Darker, dull, nonreflective
		uncoated	74.7	74.7			
6	Thermoplastic binder (TPB)	coated	0.1				
		uncoated	88.4	884.0			
7	TPB + consolidant	coated	0.5				
		uncoated	99.9	200.0			
8	SO-3 additive	coated	1.7				
		uncoated	74.9	43.8			
9	Raw tung oil coating	coated	0.9		1.66		Yellowish, dull, nonreflective
		uncoated	67.7	75.2	10.00	6.01	
10	Raw tung oil soaking	coated	0		4.29		Yellowish, dull, nonreflective
		uncoated	109.9	∞	17.00	3.96[b]	
11	TPB	coated	0				Dull, nonreflective, little change in color
		uncoated	94.8	∞			
12	TPB	coated	0.3				Dull, nonreflective, little change in color
		uncoated	119.7	399.0			
13	TPB	coated	1.3				Dull, nonreflective, little change in color
		uncoated	118.9	91.5			
14	TPB	coated	0				Dull, nonreflective, little change in color
		uncoated	42.1	∞			
15	TPB	coated	1.6				Dull, nonreflective, little change in color
		uncoated	116.3	72.7			

[a] Wear resistance = ratio of abrasion of uncoated surface to abrasion of coated surface.

[b] Only 34 g of raw tung oil was absorbed (normally, 50 g of raw tung oil was absorbed).

Soaking method (sample 10): Each test piece was placed in a tightly fitted cardboard frame that had been waxed with paraffin. Fifty grams of raw tung oil was poured onto each test piece and allowed to slowly infiltrate the tile.

All the consolidants used in both the coating and soaking techniques were absorbed completely by the tile samples. After treatment with tung oil, samples were observed to have a dull, homogeneous, nonreflective surface that was slightly yellowish in hue.

Tests of consolidant on Mogao grotto floor tiles

In the third part of the experiment (samples 11–15), the same consolidant used in sample 6 on Meridian Gate tiles was applied to decorative floor tiles from the Mogao grottoes. Based on the first test results, this polyurethane consolidant, a Wang-brand thermoplastic resin, demonstrated a high degree of wear resistance. The Mogao tiles, produced during the Tang and Song dynasties, are not as strong and dense as those made for the Ming-period Meridian Gate; they contain more sand, less clay, and were fired at a lower temperature.

Abrasion Tests

Abrasion test results for each tile sample are shown in Table 1. Using a road-abrasion testing machine (from the former East Germany) with a rotating steel ball, 40 kg top load was applied and rotated eighty times on the Meridian Gate samples (samples 1–10). Because they are of poorer quality, the Mogao tiles (samples 11–15), were tested under 20 kg top load and rotated forty times. The polyurethane consolidants used in samples 5–8 gave satisfactory results, especially in samples 6 and 7. These consolidants remarkably increased the wear resistance of the tiles (Fig. 1).

Even better results were observed for the tiles treated with raw tung oil (samples 9 and 10). There is almost no abrasion loss for sample 10 (Fig. 2), which was treated by the soaking method. The tung-oil coated and soaked samples were also tested in a sandblasting machine. The samples were placed at a distance of 20 cm from the spray nozzle and blasted with 6 kg cm^{-2} of air pressure for fifteen seconds. These results demonstrated that treatment with raw tung oil can effectively increase the wear resistance of ancient tile.

The Mogao test pieces (samples 11–15) coated with the Wang polyurethane consolidant used in sample 6 also gave very satisfactory results (Fig. 3).

Figure 1
Sample tiles from Meridian Gate, Beijing Palace Museum, after abrasion-resistance testing; tile consolidated with polyurethane on the left and untreated tile on the right.

Figure 2
Sample tiles from Meridian Gate after abrasion-resistance testing with raw tung oil; treated tile on left and untreated tile on right.

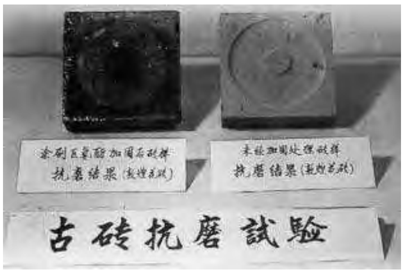

Figure 3
Samples of Mogao grottoes tiles after abrasion-resistance testing; tile consolidated with polyurethane on left and untreated tile on right.

Freeze-Thaw Tests

Freeze-thaw tests were conducted on the tile samples from the Meridian Gate (samples 1–10), using the Wang polyurethane tested in sample 6. The tiles were divided into three groups: (1) untreated samples; (2) samples coated with consolidant on 50% of the total surface area (one face and half of the four sides); and (3) samples coated on 100% of the surface area.

The dry weight of each tile was measured after the coating had been applied and allowed to dry. The samples were then soaked in water for five days. After soaking, each tile was weighed again to obtain its water-absorption rate.

To test the freeze-thaw rate, sample tiles were placed in boxes containing sticks at the bottom for support, with four tile pieces per test box. Water was gradually poured into each box until the top surface of the tile was submerged by 1–2 cm. Each box was then placed in a solution of calcium chloride at −20 °C to freeze for three hours. After this freeze period, the test boxes were transferred to a water bath at 16 °C for three hours to thaw. Temperature change was recorded with a resistance thermometer in each box. Freezing temperatures ranged from −15.95 °C to −1.35 °C, with an average of −6.9 °C. Thawing temperatures ranged from 12.5 °C to 17.7 °C, with an average of 16.6 °C. However, the volume of water in each box was too high for the samples to freeze completely in three hours.

After 40 freeze-thaw cycles, the experiment was modified to ensure effective freezing of the samples. The number of tiles in the box was reduced from four to three, and the water level in the boxes was measured at 1–2 cm above the base, rather than the top surface, of the tiles. The freeze-thaw cycle remained at an interval of three hours. Freezing temperatures measured with the new experimental procedure ranged from −11.3 °C to −3.3 °C, with an average of −7.5 °C. Thawing temperature was from 17.5 °C to 13.4 °C, with an average of 16.5 °C. The experiments were terminated after 163 cycles. Table 2 shows freeze-thaw test results for the seven samples tested. Figure 4 shows deterioration of two tile pieces after 163 freeze-thaw cycles.

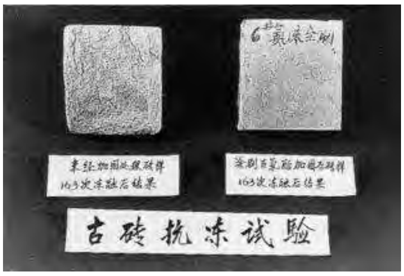

Figure 4
Polyurethane treated and untreated tiles after 163 freeze-thaw cycles. The untreated tile is on the left. The tile on the right was treated with the polyurethane used in sample 6 (Table 1).

On-Site Experiments and Results

The authors began on-site experiments at the Mogao grottoes in September 1980. Tests were conducted at three representative sites: Cave 45 (Tang dynasty), temple ruins in front of Cave 130, and Cave 328 (early Tang dynasty).

Two different consolidants were applied: raw tung oil mixed with kerosene in a ratio of 9:1; and polyurethane (the one tested in sample 6) mixed with a thinner (toluene or xylene and butyl acetate) in a ratio of 1:1.

First the tiles were cleaned and photographs were taken before coating with the consolidants. The coating solutions were then mixed on the basis of the number of tiles to be treated and the amount to be applied to each piece of tile. After treatment, photographs were taken again.

Both raw tung oil and polyurethane were applied to the tiles inside Cave 45 and outside Cave 130, and only polyurethane was used in Cave 328.

Several tiles in Caves 45 and 328 were left untreated and partially coated for comparison, and only four rows of tiles in Cave 130 were treated.

Raw tung oil penetrated rapidly and was readily absorbed; it took only twenty-four hours for the tiles at the site to absorb the same amount of oil that was used in the laboratory. During application of the polyurethane, permeation gradually became more difficult because of the evaporation of the thinner, with only half the amount of consolidant penetrating the tiles at the site as compared with the laboratory test samples.

After more than ten years of observation of natural abrasion at the site, no further wear of the treated tiles has been observed, whereas obvious wear has been observed on the untreated tiles. Thus, results show that these two consolidants were ideal agents for the protection of floor tiles in situ.

Conclusions

Compounds formed on the surface of tiles treated with polyurethane consolidants can improve the wear resistance of ancient tiles. Of these, the polyurethane used in samples 6 and 7 (Table 1) has produced the most outstanding results.

Results demonstrate that raw tung oil, a traditional material for the treatment of decorative tiles in China, is as effective as—and sometimes even better than—the best abrasion-resistant polyurethane consolidant studied in the testing project.

Table 2 Freeze-thaw test results

				Weight change after freeze-thaw test									Appearance
				After 40 cycles			After 100 cycles			After 163 cycles			
Tile sample number	Number of surfaces coated	Water absorption (%)	Initial weight (g)	Weight (g)	Weight change (g)	Percent of loss	Weight (g)	Weight change (g)	Percent of loss	Weight (g)	Weight change (g)	Percent of loss	
1	0	13.8	1675	1672	−3	0.30	1560	−115	6.87	1380	−295	17.61	Tile surface (1–3 mm) peeled off after 70 cycles.
2	0	14.3	1715	1720	+5		1710	−5	0.29	1690	−25	1.46	Tile surface (1 mm) started to peel after 70 cycles.
3	0	13.2	1890	1900	+10		1765	−125	6.61	1655	−245	12.96	Tile surface (1–2 mm) started to peel after 60 cycles.
4	1+[a]	14.8	1680	1685	+5		1660	−20	1.2	1620	−60	3.57	Untreated surface started to peel after 70 cycles.
5	1+[a]	14.5	1700	1710	+10		1710	+10		1690	−10	0.59	Untreated surface started to peel after 140 cycles.
6	6	15.8	1650	1680	+30		1670	+20		1680	+30		No deterioration observed.
7	6	13.7	1705	1725	+20		1720	+15		1720	+15		No deterioration observed.

[a] One full surface was coated plus half of each of the adjacent four sides of the tile.

Even in regard to the poorer quality tiles at the Mogao grottoes, coating with consolidants has greatly improved their wear resistance. On-site experiments also suggest that consolidation can be easily carried out in the field and that use of either coating material satisfies a fundamental conservation principle of retaining the original appearance of materials.

In addition, polyurethane coating was shown to increase the ability of tiles to withstand freezing and thawing with less deterioration of the surface.

In March 1988, an evaluation team from the Unesco World Heritage Committee visited the Mogao grottoes for two days. Team members raised several issues concerning the conservation of the site and made a number of suggestions. The protection of the floor tiles was one of the items mentioned in their report (Unesco 1988: Item 94). They pointed out that replacing the floor tile with concrete would change the original grotto structure and would also disturb the microenvironment inside the cave. Environmental monitoring was suggested for caves with original floor tiles as well as for those with concrete floors. The report also proposed that the ancient floors be conserved by placing mats and other protective pads in areas that incur heavy traffic.

In accordance with the evaluation team's suggestions, environmental monitoring of caves with both types of floors are being conducted. As for floor mats or pads, it was felt that these may be useful for tile protection but would limit visitors' ability to appreciate the aesthetic tile patterns of the floors. The most suitable approach, therefore, is still to treat the tiles with consolidants and other protective coating materials.

Note

1 Additional information was not available on the chemical nature and source or manufacturer of consolidants tested. Ed.

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Unesco World Heritage Committee

1988 *Mission Report: People's Republic of China, 21 March–5 April 1988. World Heritage Convention, Unesco.* Rome: International Centre for the Study of the Preservation and the Restoration of Cultural Property (ICCROM).

A Chinese Wall Painting and a Palace Hall Ceiling

Materials, Technique, and Conservation

Sally Malenka and Beth A. Price

The Yuan dynasty wall painting and Ming dynasty palace hall installed in the Philadelphia Museum of Art provide, as was the intent of their acquisition, impressive architectural settings for the display of Chinese objects. The development and implementation of a conservation treatment for the painted ceiling of the palace hall initiated a study of materials and techniques of Chinese architectural painting. Although the wall painting represents a different painting tradition, it offered a convenient comparison with a similar paint structure. The materials of both the wall painting and palace hall ceiling were studied using a complement of analytical methods: visible-light, fluorescence, and polarized-light microscopy (PLM), electron probe microanalysis (EPMA), X-ray diffraction (XRD), Fourier-transform infrared microspectroscopy (FT-IR), gas chromatography-mass spectrometry (GC-MS), reversed-phase high-pressure liquid chromatography (RP-HPLC), and wet-chemical testing.[1] The history, the technique and materials, and the conservation treatments for the wall painting and palace hall ceiling are described here.

The Wall Painting

History

The Yuan dynasty wall painting depicts an assembly of bodhisattvas, cosmic deities, civil and military guardians, and donors (Fig. 1). It was purchased by the museum in 1924 through George Crofts and Company in Tianjing, China. The wall painting was removed from a partially destroyed temple near Xinxiang in Henan Province (George Crofts and Co. 1924, 1925). It is now displayed in a gallery built from parts of a Ming dynasty temple.

Technique and materials

The technique and materials of the wall painting are consistent with those published for other wall paintings (e.g., Gordon and Phillimore 1984; Hanna, Lee, and Foster 1988). Under magnification, an underdrawing for

Figure 1
Wall painting, Yuan dynasty (1260/80–1368). Width 4.5 m, height 2.8 m. Philadelphia Museum of Art, 1925-98-1. Given anonymously in memory of Langdon Warner.

the layout of the stylized imagery was visible along damaged edges. Folds of garments and lines on faces were not underdrawn but executed in black only after the color fields were painted.[2] The raised ornamentation on garments, jewelry, and attributes were produced before the fields were painted; gilding was one of the final steps.[3]

The range of effects, which are produced by techniques characteristic of a watercolor medium, is masterful. Volume is given to forms by the transition of a single color from dark to light. The texture of leathery skin on the mask of a guardian figure's belt is evoked with concentric circles of large and small dots of paint. Subtle shadows in flesh areas are created with dark underlayers or with black pigments added to white.

Cross-section analysis shows the painting to be composed of three distinct layers: a coarse render, a fine white preparation layer, and a paint or presentation layer. There is no evidence of repainting. A backscattered electron microscope image of a typical cross section is shown in Figure 2. Table 1 summarizes the pigments and grounds identified in these layers.

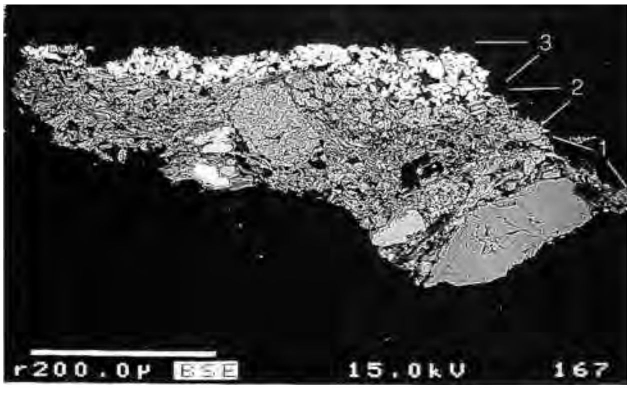


Figure 2
A backscattered electron microscope image from the Yuan dynasty wall painting showing (1) coarse render, (2) clay preparation layer, (3) red-lead paint layer.

Table 1 Pigments and grounds identified in the Yuan dynasty wall painting.[a]

Layer	Mineral name	Chemical formula	XRD-JCPDS #
Render	clay:		[b]
	kaolinite	$Al_2Si_2O_5(OH)_4$	[c]
	montmorillonite	$(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$	[c]
	quartz	SiO_2	33-1161
	calcite	$CaCO_3$	24-27
Preparation	clay:		[b]
	muscovite	$KAl_2(Si_3Al)O_{10}(OH)_2$	21-993
	biotite	$K(Mg,Fe)_3(Al,Fe)Si_3O_{10}(OH)_2$	2-45
	quartz	SiO_2	33-1161
Raised ornament	calcite	$CaCO_3$	24-27
Paint			
red	red lead and/or	Pb_3O_4	8-19
	vermilion	HgS	[d]
blue	azurite	$Cu_3(CO_3)_2(OH)_2$	11-682
green	atacamite and	$Cu_2Cl(OH)_3$	25-269
	botallackite	$Cu_2Cl(OH)_3$	8-88
white	lead white	$2PbCO_3 \cdot Pb(OH)_2$	
flesh	lead white with	$2PbCO_3 \cdot Pb(OH)_2$	13-131
	red lead and	Pb_3O_4	8-19
	charcoal black	C	[d]
	lead white with	$2PbCO_3 \cdot Pb(OH)_2$	13-131
	red lead and	Pb_3O_4	8-19
	vermilion and	HgS	[b]
	charcoal black	C	[d]
black	charcoal black	C	[d]

[a] All samples identified by PLM and EPMA (except where noted by "d"); confirmation by FT-IR or XRD as noted.

[b] Identified by PLM and EPMA.

[c] Identified by PLM, EPMA, and FT-IR.

[d] Identified by PLM.

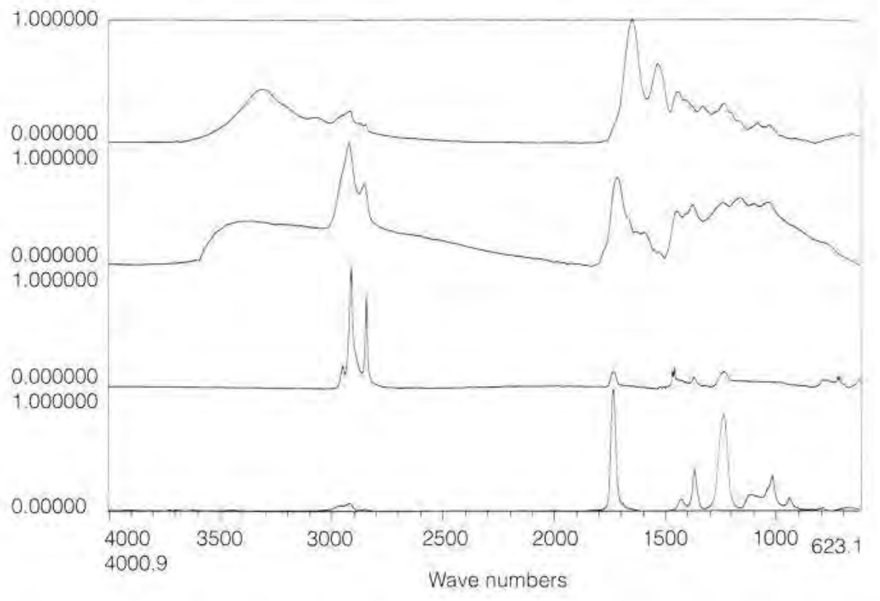
The coarse render consists primarily of clay, quartz, calcite, and fibers. The fine white preparation layer contains clay and quartz, with less iron than that of the render. The paint palette is restricted to a few colors.

Three kinds of organic media were detected (Fig. 3). Their identification was complicated by the impregnation of the painting with polyvinyl acetate (PVAc), which was detected in each of the layers. (See treatment description that follows.) All of the layers contained proteinaceous material.[4] In addition, there were trace quantities of conifer resin in the fine white preparation layer,[5] and a resin in the gilding mordant. Wax was found associated with the gilding layer.

Conservation treatment of the wall painting

When the wall painting was removed from its original site, it was cut into eighty sections, backed with paper, and shipped to the museum (Fig. 4). The removal of the painting from its architectural situation initiated a series of decisions, within a Western paintings conservation tradition, as described here.

Figure 3
Infrared spectra from the Yuan dynasty wall painting (top to bottom): proteinaceous material in coarse render, resin in gilding mordant, wax associated with gilding, and PVAc from the 1930 restoration.



The painting was examined, treated, and reassembled by George Stout and Rutherford Gettens in 1930 at the Fogg Art Museum at Harvard University (Stout and Gettens 1930, 1931).[6] A 5% solution of PVAc was sprayed on the front, and cracks and holes were filled with a mixture of clay, sand, and water; the surface was then brushed with a 20% solution of PVAc. The painting was faced with hide glue, paper, and muslin, and the back was scraped to a thickness of 1–2 mm. After the sections were lined with linen and treated with PVAc, they were held in a press for forty-eight hours[7] and then glued to five wood panels for gallery installation. Finally, the facing was removed with water, and excess PVAc was reduced with toluene.

Figure 4
Sections of the wall painting in China, circa 1925.

PVAc was a new material to conservation in the 1930s. Gettens himself became aware of it through publications in 1928 (Gettens 1935:16). The long-term properties of PVAc as a surface consolidant were unknown, but it compared favorably with alternative contemporary resins. PVAc was colorless and retained the matte surface quality of an aged and untreated painting (Gettens 1935:19, 26, 27).

Since its treatment, the wall painting has remained stable with no cleavage from the wood support. The ornamentation is flattened, and the entire painting is smooth and hard. On close examination of the surface, residual PVAc is soft and visible with entrapped dust and dirt. The saw gaps between cut sections were integrated with a toned fill but were not inpainted.[8] This choice, reflecting the collection history of the piece, remains the preference of the curator today. There are no plans at this time for additional conservation of the wall painting.

The Palace Hall Ceiling

History

The ceiling of the Ming dynasty palace hall is painted with conventional flowers of the four seasons, stylized dragons and clouds, and delicately rendered mythical animals (Fig. 5). The palace was located in Wangdoren Hutong in northeastern Beijing. According to oral tradition, it was built by a chief eunuch of the emperor Tianqi (1621–27) (Jayne 1929:27–28). At the end of the nineteenth century the Empress Dowager (1835–1908) confiscated the palace and gave it to her younger brother (Smith 1901:535–36). The hall was purchased in 1928 by Horace H. F. Jayne for the museum. From photographs of the palace in situ and in eyewitness accounts, the palace complex had been neglected and had fallen into ruin

Figure 5
Palace hall, Ming dynasty (1368–1644), circa 1621–27. Length 14 m, width 11 m, height 11 m. Philadelphia Museum of Art, 1929-163-1. Given by Edward B. Robinette. Note the side door in center of photograph; the installation of the hall as a museum gallery dictated a change in the position of the side doors that had led into two rooms not acquired by the museum.

(Roberts 1940:23). The palace hall is now the setting for furniture and precious objects from the Ming and Qing dynasties.

Technique and materials

The ceiling is constructed of wood from a species in the red pine group, possibly *Pinus massoniana* (Miller 1992). Areas of design were first blocked out in large color fields, and then the painted decorations were successively applied. The design is formally arranged but loosely executed.

The wood is covered with a coarse render, followed by a fine preparation of dark or white layers or both. Cross-section analysis shows three major paint campaigns and numerous partial campaigns. Figure 6 illustrates a representative cross section. Three complete sequences were found on the ridge beam, which is the highest center beam. Most cross sections examined included the second and third campaigns or some variation of them. Table 2 summarizes the stratigraphy, pigments, and grounds identified in these layers.

In the earliest paint campaign on the ridge beam, green, blue, and red are found with raised and gilded ornamentation. On the main beams, the earliest campaign is red with raised and gilded ornamentation in a geometric pattern. This pattern is stylistically different from the cloud and floral motifs now seen on the main beams.[9]

The palette of the second campaign is narrower than that of the first and third campaigns. Blue, green, black, and white predominate. Only one section of red and one of yellow were found, and they may be associated with other partial repaintings.[10]

The third campaign is the current surface. A coarse render is followed by a preparation layer of white, blue, and yellow. The palette includes the colors of the second campaign. In addition, red lead was used extensively, and red and yellow lakes were found in the flower designs.

The use of malachite, azurite, and vermilion in the early campaigns, compared with the use of copper chloride greens, organic dyes, and red lead in later layers, may reflect the relative cost or availability of

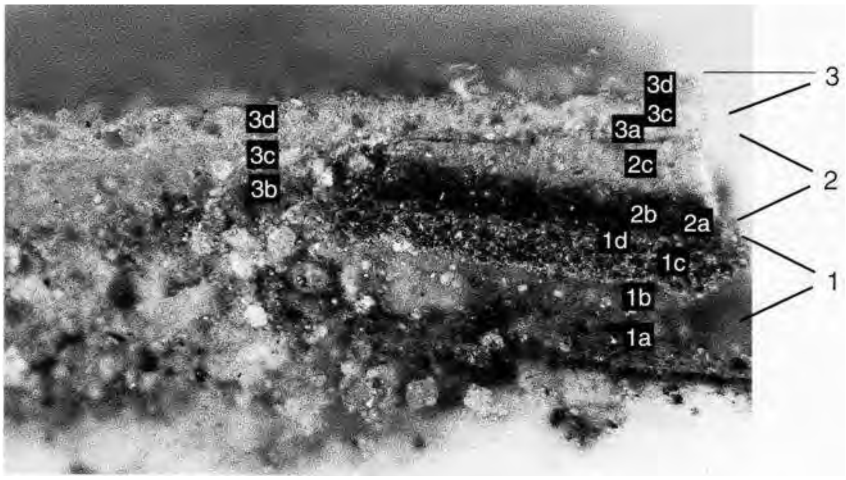


Figure 6
Cross section from the ridge beam of the palace hall (10× object ≈ 435 m thick). The cross section shows three paint campaigns. Campaign 1: (1a) coarse render, (1b) white preparation layer, (1c and d) blue and red paint layers. Campaign 2: (2a) coarse render, (2b) black preparation layer, (2c) green paint layer. Campaign 3: (3a) polysaccharide layer, (3b) coarse render, (3c) white, blue, yellow preparation layer, (3d) green paint layer.

Table 2 Pigments and grounds identified in the paint campaigns of the Chinese palace hall ceiling[a]

Layer	Mineral name	Chemical formula	XRD-JCPDS #
FIRST CAMPAIGN			
Render	clay		[c]
	quartz	SiO_2	[c]
Preparation	calcite	$CaCO_3$	24-27
Raised ornament	calcite	$CaCO_3$	24-27
Paint			
green	malachite and	$Cu_2(CO_3)(OH)_2$	10-399
	atacamite	$Cu_2Cl(OH)_3$	25-269
blue	azurite	$Cu_3(CO_3)2(OH)_2$	11-682
blue	dye		[d]
red	vermilion	HgS	6-256
SECOND CAMPAIGN			
Render	clay:		[c]
	montmorillonite	$(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$	[b]
	kaolinite (minor)	$Al_2Si_2O_5(OH)_4$	[b]
	quartz	SiO_2	[b]
	gypsum (minor)	$CaSO_4 \cdot 2H_2O$	[b]
Dark preparation	clay:		[c]
	montmorillonite	$(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$	[b]
	kaolinite (minor)	$Al_2Si_2O_5(OH)_4$	[b]
	quartz	SiO_2	[b]
White preparation	clay:		[c]
	muscovite	$KAl_2(Si_3Al)O_{10}(OH)_2$	[b]
	quartz	SiO_2	33-1161
Paint			
green	atacamite and/or	$Cu_2Cl(OH)_3$	25-269
	botallackite	$Cu_2Cl(OH)_3$	8-88
blue 1	lead white and	$2PbCO_3 \cdot Pb(OH)_2$	13-131
	calcite and	$CaCO_3$	24-27
	dye		[d]
blue 2			[e]
red	red lead	Pb3O4	8-1
black	carbon	C	[f]
white	lead white	$2PbCO_3 \cdot Pb(OH)_2$	13-131
yellow	calcite and	$CaCO_3$	24-27
	dye		[d]
THIRD CAMPAIGN			
Render	calcite	$CaCO_3$	[b]
	gypsum	$CaSO_4 \cdot 2H_2O$	[b]
	quartz	SiO_2	[b]
Preparation			
white,	calcite and	$CaCO_3$	24-27
blue,	dyes		[d]
yellow			
Paint			
green	atacamite and/or	$Cu_2Cl(OH)_3$	25-269
	botallackite	$Cu_2Cl(OH)_3$	8-88
blue	lead white and	$2PbCO_3 \cdot Pb(OH)_2$	13-131
	calcite and	$CaCO_3$	24-27
	dye		[d]
orange-red	red lead	Pb_3O_4	8-19
black	carbon	C	[c]
white	lead white	$2PbCO_3 \cdot Pb(OH)_2$	13-131
red	red lake		[d]
yellow	yellow lake		[d]

[a] All samples identified by PLM and EPMA (except where noted by [d]); confirmation by FT-IR or XRD as noted.
[b] Identified by PLM, EPMA, and FT-IR.
[c] Identified by PLM and EPMA.
[d] Dyes not included in study.
[e] Not conclusively identified: EPMA detected Si, K, Mg, minor Al, Fe, and no Co, Cu. SiO_2 confirmed by XRD.
[f] Identified by PLM.

these pigments. Also, large timbers were valuable; the ones in the palace hall may have been reused from another structure and may have an independent paint history.

In all layers, proteinaceous material was found to be the major organic phase.[11] In the coarse render, GC-MS detected trace levels of drying oil and minor quantities of conifer resin.[12] In the preparation and paint layers, minor quantities of conifer resin were also detected.[13]

An unpigmented layer between the second and third paint campaigns was characterized as a polysaccharide containing starch granules, possibly rice paste, with a minor oil component. This layer was probably applied to improve adhesion of the render of the third campaign. FT-IR of the gilding mordant layer detected a resin and proteinaceous glue, but this identification requires further investigation.

Conservation of the palace hall

The paint layer is flaking primarily at the wood-ground interface; approximately 75%, or 307 m^2, of the ceiling requires some treatment (Fig. 7). In order to select appropriate adhesives for the treatment and to develop a comprehensive conservation strategy, a testing and planning phase was carried out.

Seven test areas representative of failed paint layers were selected. Written records and photographs documented the condition before and after treatment. A section in each test area was left untreated as a control.

The adhesives tested included acrylic resins (Rhoplex AC-33, Acryloid B-72, and Acryloid B-67); PVAc-derived polymers (Bakelite AYAF and AYAT, Butvar B90 polyvinyl butyral resin, Gelvatol polyvinyl alcohol, and BEVA 371); cellulose ethers (Methocel A4C and Klucel G); and proteinaceous glues (isinglass and gelatin). Solvents were selected to control working properties. Adhesives in water, ethanol, or mixtures of both were preferred because they softened the paint, allowing it to be returned to plane, and had low toxicity. The adhesives were introduced under and through the paint layer with a brush or syringe.

Figure 7
Ground-facing surface of a main beam from the palace hall illustrating the flaking and loss of paint.

The test areas were evaluated at intervals of one month and two years by assessing adhesion of the paint to the wood and visible alterations to the surface quality of the paint. Change in saturation of color or the matte quality of the paint was undesirable. It was found that many of the adhesives stained the wood and saturated the color, especially the layer of blue-dyed calcite and lead white.

Based on the test results, Methocel A4C (1–2% in 50/50 ethanol/water) and Klucel G (1–2% in ethanol, and 1–2% in 60/40 toluene/ethanol) (all w/v) were used for the treatment. Methocel A4C did not saturate the wood and paint layer, except for the blue colors; the adhesion was sufficient within the museum environment, which is maintained at approximately 21 °C and 50% relative humidity. Klucel G was the only adhesive tested that did not saturate the blue areas and was therefore used selectively, although in general Klucel G may be considered less stable than Methocel A4C (Feller and Wilt 1990:94–95).

The treatment procedure included removal of particulates on the surface with dry brush and vacuum, removal of particulates from behind the detached paint layer with a brush dampened with mineral spirits, injection of the adhesive with a syringe, and readhesion of the paint with a hot spatula. This procedure was modified as needed to suit the condition of the paint layer.

The project was scheduled to be completed at the end of 1996. A representative area will be left untreated for future materials analysis and as a reference for comparison to treated areas. Long-term care will include monitoring the adhesion in areas that were documented in detail, minimizing dust accumulation, and maintaining low light levels as well as a stable temperature and relative humidity.

Conclusion

The materials of the wall painting and palace hall ceiling have many parallels, including a narrow palette, raised gold ornamentation, coarse and fine grounds, and proteinaceous binders with trace levels of conifer resins. The use of different materials over time in the palace hall might suggest a change in the cost or availability of particular pigments; studies of similar architecture would provide useful comparisons.

The materials analysis and the testing and evaluation of treatment options, including a review of previous treatments, were considered essential in developing and implementing the conservation treatment of the palace hall ceiling.

Acknowledgments

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and Joe Mikuliak, Philadelphia Museum of Art. The treatment planning phase for the palace hall ceiling was supported in part by the National Endowment for the Arts, a federal agency. The conservation treatment of the palace hall ceiling was supported in part by the Women's Committee of the Philadelphia Museum of Art and by the Institute of Museum Services, a federal agency that offers conservation project support to U.S. museums.

Notes

1 Instruments used: Zeiss Universal Research polarizing microscope; Wild Leitz Laborlux S microscope; Cameca SX50 electron probe microanalyzer equipped with wavelength dispersive spectrometers (WDS) and Princeton Gamma Tech IMIX solid-state detector; Philips PW1729 X-ray generator equipped with a PW1840 diffractometer and Gandolfi cameras; Nicolet 510P FT-IR spectrometer bench and Nic-Plan microscope with a Spectra-Tech Micro Sample Plan with diamond windows; Fisions VG Trio 2000 MS equipped with a Hewlett-Packard 5850 Series II GC; Hewlett-Packard MS Engine with HP5890 Series II GC; and Waters Picotag amino acid analysis system.

2 A section of the painting that was not installed was examined by infrared reflectography. A brush stroke could be seen as a guide for the placement of the proper left eyebrow of the figure.

3 In contrast, Hanna, Lee, and Foster (1988:34) found the gilding below, not above, the painted decoration for a painting of three bodhisattvas from 1424, Shanxi Province.

4 Proteinaceous material was characterized by FT-IR: NH stretch 3309 cm^{-1}; amide II overtone 3078 cm^{-1}; amide I (CO absorption) 1657 cm^{-1}; amide II (NH_2 deformation) 1533 cm^{-1} (Bellamy 1975:233, 250–57). Selected samples were confirmed by amino acid analysis. The amino acid composition of the paint layer included hydroxyproline and had a profile characteristic of an animal-skin glue (Halpine 1992). The coarse render contained other amino acids not accounted for by the animal-skin glue. It should be noted that hide glue was used for the facing as discussed in the treatment section.

5 GC-MS analysis in the selected ion monitoring mode (SIM) detected a molecular ion at mass 314 and the base peak at mass 239, suggesting the presence of methyl dehydroabietate, the methylated derivative of dehydroabietic acid, a diterpenoid present in conifer resins (Mills and White 1982).

6 Many wall paintings acquired by museums in North America and Europe were treated in a similar manner (e.g., Stout and Gettens 1932).

7 Two 2.54 cm diameter fragments of the painting were saved at this stage of the treatment. They are very rigid and glossy.

8 See Stout (1941:105) for a discussion of compensation, including examples from a Chinese wall painting.

9 It is unclear whether the first paint campaign on the main beams is contemporary with the first campaign on the ridge beam. For example, vermilion and gold are found in both; however, the sequence and composition of grounds are different.

10 These anomalous layers may reflect partial campaigns or a sampling bias.

11 See note 4. Amino acid analyses detected more than one proteinaceous material but included animal-skin glue.

12 The dicarboxylic acid methyl ester, dimethyl nonanedioate (azelate) molecular ion, was found with peaks observed at masses 185, 152, 111, 83, and 74, indicating the presence of an aged oil. Trace levels of methyl-7-oxo-dehydroabietate, an oxidation product of pine resin, were detected with peaks at masses 328 and 253 (Mills and White 1982).

13 GC-MS analysis of the preparation layer of the first paint campaign revealed the presence of abietic and pimaric acid methyl ester analogues. In nature, these compounds appear as the free

acids, with trace quantities of the esters occurring in a true bled conifer resin. Significant amounts of these esters may have accrued by pyrolysis of the wood in the collection or production process (White 1993).

Materials and Suppliers

Acryloid B-72, Acryloid B-67, Rhoplex AC-33, Conservation Materials, Ltd., 1165 Marietta Way, P.O. Box 2884, Sparks, NV 89431 (manufactured by Rohm and Haas Company, Philadelphia, PA).

Bakelite vinyl acetate AYAF and **AYAT**, Conservation Materials, Ltd. (manufactured by Union Carbide Corporation/ Chemicals and Plastics, 270 Park Avenue, New York, NY 10017).

BEVA 371, Conservator's Products Company, P.O. Box 411, Chatham, NJ 07928; or Adam Chemical Co. Inc., 18 Spring Hill Terrace, Spring Valley, NY 10977.

Butvar B90 polyvinyl butyral resin, Conservation Materials, Ltd. (manufactured by Monsanto Polymers and Petrochemical Co., 800 N. Lindbergh Blvd., St. Louis, MO 63167).

Gelvatol polyvinyl alcohol, Conservation Materials, Ltd.

Klucel G, Aqualon Company (A Division of Hercules), Wilmington, DE 19894.

Methocel A4C, The Dow Chemical Company, Midland, MI 48674.

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The Conservation of Tempera Mural Paintings and Architectural Finishes

Constance S. Silver

The artistic patrimony of the Silk Road is all the more remarkable when one recalls that its monumental mural paintings and sculpture are derived primarily from Neolithic traditions that stem from simple clay-based technologies. For example, characteristic mud-brick construction, cut-stone masonry, and grotto surfaces were covered with mud renderings, upon which mural paintings and other decorative finishes were executed. Most of the pigments also contain clays. The paint media were obtained from plant gums, faunal glues, and other natural materials (Mora, Mora, and Philippot 1984:82–83).

Although separated by distance and culture, there are many mural paintings in the United States that share technical similarities with those of the Silk Road. The prehistoric and historic mural paintings of Native Americans of the Pueblo culture of the American Southwest are technically the closest. Classically Neolithic, they were painted with naturally occurring pigments in tempera media applied to mud and clay renderings. There are also tempera mural paintings in the Western tradition that date from the eighteenth, nineteenth, and twentieth centuries, although these are rarely executed on clay-based renderings. The following discussion focuses on minimum intervention—a key principle of modern conservation—for the treatment of monumental mural painting in tempera media, and reviews four recent case histories from the United States.

Minimum Intervention in the Treatment of Tempera-Based Murals

The principal objectives of minimum intervention in the treatment of tempera-based mural paintings are the retention of original materials and their original optical qualities and the retention of the mechanical equilibrium of rendering, preparation, and paint. Consequently, modern synthetic materials of conservation, which generally differ radically from traditional materials, are employed only when there are no other practical options.

However, there are additional technical and philosophical reasons for minimum intervention. Mural paintings are inherently problematic for

conservators because they are a component of generally complex building systems that include the architectural/structural support, the materials of preparation and paint layers, the ever-changing interior and exterior environments in which the structure and murals exist, and the impacts from human use and misuse. All elements of the system must remain compatible if the mural painting is to survive in an undamaged state. Unfortunately, it is quite easy for any building system to become destabilized, and it is impossible to predict when instability may occur. It is also acknowledged that many conservation treatments have proved unsatisfactory or incompatible over time, in spite of the best modern climate-control systems. In this regard, the porous nature of the component materials of the murals of the Silk Road, and of similar tempera-based murals, makes complete removal of any poorly performing conservation materials virtually impossible.

Thus, minimum intervention is physically prudent. It is also philosophically attractive because the murals of the Silk Road—like those of the prehistoric Southwest—are the material record of unique moments in human history. When these murals are infused with modern synthetic materials, they are changed forever—even if the treatment accomplishes its goals. The following case histories from three regions of the United States—the Southwest, the Central Atlantic, and the Northeast—illustrate the viability of minimum intervention for the conservation of tempera mural paintings (Fig. 1).

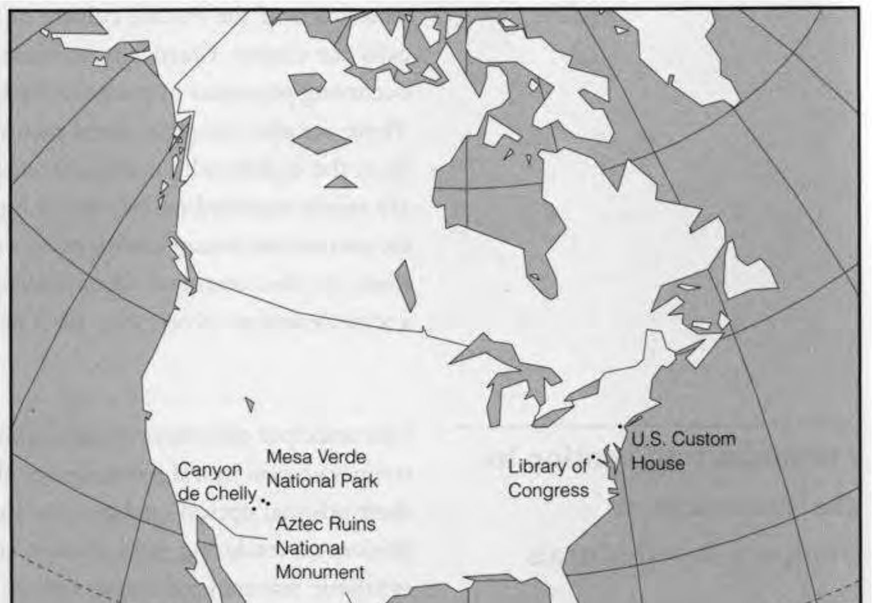

Figure 1
Map showing the location of the sites discussed.

Prehistoric Mural Paintings and Architectural Finishes in the American Southwest

The prehistoric agrarian culture of the American Southwest culminated around 1250 C.E., in complex masonry villages constructed in huge caves, the world-famous cliff dwellings. By about 1350 C.E., the area had been abandoned by its prehistoric inhabitants, for reasons still unknown. Extensive paintings survive on the prehistoric architecture at such sites as Mesa Verde National Park, Colorado; and Canyon de Chelly, Arizona. Briefly summarized, the most complex architectural finishes are composed of a first rough coat of mud mortar applied directly to the masonry, and sometimes to the stone face of the caves. A second finish coat, of finer texture, was applied to the rough coat. This stratum is the surface for the painting. Often, a ground of white clay was applied in preparation for painting. The palette was simple, consisting of a small number of mineral pigments. The most outstanding mural paintings were executed in subterranean chambers called kivas, used for ceremonial purposes (Smith 1952).

In 1981, a field study was undertaken in Mug House Ruin, Mesa Verde National Park, a site administered by the National Park Service. The objective was to develop methods for the conservation of the architectural finishes and to test the conservation treatments in the field over several years. The research design was based on an observable fact: after eight hundred years in uncontrolled environments, in the absence of human contact, the murals had remained in remarkably good condition. Clearly, this "system" of architecture, architectural finish, and environment had proved itself compatible over many centuries. Where unaffected by human intervention, deterioration of the architectural finishes resulted largely from the fatigue and desiccation of the component materials over time. Therefore, modern materials of conservation were judged an option of last resort because they might introduce a destabilizing element into the generally stable system, in addition to changing the original materials' composition forever.

However, the murals of the subterranean kivas were actively deteriorating from human intervention: they had been excavated in the early 1960s and left exposed, the surface of the murals acting as the site of evaporation for groundwater moving through the masonry. Several conservation problems had developed and become very serious: detachment of rendering from the wall; delamination between strata of the rendering; friable rendering; flaking paint; efflorescence; root penetration; burrowing insects and rodents; and surface dirt.

It was posited that water would be an effective conservation material because of its capacity to relax and replasticize the brittle and deformed clay-based rendering and paint. This would permit compaction and cohesion of the delaminated strata of the rendering and their reattachment as a cohesive unit on the masonry. Water also enhances the bond between paint and rendering, perhaps also by reactivating any remains of desiccated original media that might still be present.

Pilot conservation treatments were carried out on one kiva and on one standing wall of Mug House in 1981 (Fig. 2) (Silver 1991). Briefly summarized, the treatment to stabilize rendering and paint entailed temporary attachment of supportive wet-strength tissue facings to the surface,

Figure 2
Mug House Ruin, Mesa Verde National Park, Colorado.

using water applied by brush. This was followed by spraying of water, until the rendering became malleable. A mixture of 50% water and 50% isopropyl alcohol was injected between the detached rendering and the masonry, followed by injections of diluted polyvinyl acetate emulsion.[1] The treated area, now a cohesive unit, was pressed back onto the plane on the wall and allowed to dry under pressure for twenty-four hours. The adhesive was the only synthetic material used in this treatment because no other practicable category of material was available. However, it was used as a thin stratum in discrete areas of detachment between the surface of the masonry and the rendering. No synthetic materials were infused into the fabric of the mural nor applied to its surface.

After nine years, the treated areas had remained stable. Based on these results, two comprehensive projects to conserve very unstable mural paintings were carried out at Aztec Ruins National Monument, New Mexico (Silver, Snodgrass, and Wolbers 1993). Aztec Ruins National Monument is a prehistoric site administered by the National Park Service. The first project was undertaken in 1990 to stabilize the mural paintings in Room 156, a roofed masonry structure (2.8 × 3.1 × 3.4 m high). Although roofed, there had been leaks—causing serious detachment of the mural paintings from the masonry walls—erosion, and considerable deposition of mud on the painted surfaces.

The murals were stabilized using the methods developed in 1981 during the pilot treatments at Mesa Verde National Park. However, Rhoplex AC-33, an acrylic emulsion adhesive, was substituted for polyvinyl acetate emulsion because there is some evidence that it will age better in the field. The mud was removed with various mechanical methods. The murals have remained stable.

The mural painting in Room 117 of Aztec Ruins National Monument was treated in 1992 (Fig. 3). Measuring about 1 × 1.3 m, it is located on a fragmentary wall that had been partially exposed to the ele-

Figure 3
Mural painting in Room 117, circa 1300 C.E., 1 × 1.3 m, Aztec Ruin National Monument, New Mexico.

ments since excavation around 1920. The mural, composed of horizontal fields of white and red paint, is unusual and important because many anthropomorphic, zoomorphic, and geometric forms were etched into the upper white field.

The mural had deteriorated and become very unstable due to its semiexposed position and to artificial and adverse changes in drainage patterns. The instability was exacerbated by the effects of heavy coatings of shellac and cellulose nitrate, which had been applied as consolidants in the past. These coatings were unsightly because they had consolidated dirt on the surface and had blanched (i.e., turned milky and opaque). More disturbingly, however, the coatings were contracting, causing the painted stratum to curl and detach from the mud rendering.

A treatment to remove the coatings was developed by application of solvent mixtures through Gore-Tex[2] and wet-strength tissue. The Gore-Tex appears to exert a poultice effect, drawing the dissolved coatings from the mural and depositing them on the tissue. However, laboratory examination showed that some adhesive remains fixed below the painted surface, again indicating that it is impossible to remove all consolidants from this type of porous material.[3] The murals were then stabilized with the treatment used in Room 156, mentioned above. The final step of the project entailed controlled backfilling as the only viable and cost-effective way to protect the mural from the elements.

Tempera Mural Paintings by Candido Portinari in the Library of Congress

The Library of Congress in Washington, D.C., maintained by the architect of the U.S. Capitol, has recently been renovated and restored. On 12 February 1990, a frozen pipe ruptured above the Hispanic Reading Room. Water flooded the area above the room and soaked into the mural *Mining for Gold,* painted in 1941 by the Brazilian artist Candido Portinari (1903–62) in a tempera technique on a lime-based plaster (Fig. 4). According to his son, Portinari painted with Totain glue, a form of rabbit-skin glue still used today. Laboratory analyses confirmed the presence of rabbit-skin glue, but also suggested that egg albumen might have been used, as well, in a very limited way.[4]

Figure 4
Candido Portinari, *Mining for Gold,* 1941, 5 × 6 m, Jefferson Building, Library of Congress, Washington, D.C.

Following the flood, the ambient conditions of the room and the water content of the mural painting were monitored. The relative humidity in the room stabilized about three weeks after the flood. The mural was allowed to dry slowly for several months. The flooded cavity wall was opened, and fans maintained circulation of air in the room and in the wall. Although the mural had been soaked, it remained remarkably stable as it dried. However, the paint did powder and flake in many areas. Salts composed of sodium sulfate, sodium chloride, and sodium carbonate effloresced in some areas.

A conservation treatment was carried out in April 1991. Salts were removed on a cotton swab moistened with saliva. Powdering paint was consolidated with rabbit-skin glue diluted 1:18 in water, and applied as a fine mist. Areas of lost paint were inpainted with pure powdered pigments in water. The mural painting has remained stable since treatment.

The Murals of Reginald Marsh in the U.S. Custom House, New York City

One of the most outstanding cycles of mural paintings in the United States was executed in 1937 in the rotunda of the U.S. Custom House, New York City, by modern American master Reginald Marsh (1898–1954) (Fig. 5). The sixteen murals show alternate scenes of the port of New York as it appeared in 1937, with trompe l'oeil portraits of important historic explorers. Laboratory analyses were positive for protein, supporting archival documents that suggested that Marsh employed a tempera medium composed of pigments mixed in limewater and skim milk applied to a dampened lime plaster; however, Marsh's idiosyncratic technique has not been identified with complete certainty.

Figure 5
The murals of Reginald Marsh, painted in 1937 in the rotunda of the U.S. Custom House, New York City.

From 1937 until 1970, the rotunda was a busy office space. With the exception of heat in the winter, the environment remained uncontrolled. From 1970 until 1991, the building was abandoned and unheated, and the roof often leaked. Thus, when each mural was individually examined in 1990, preparatory to the renovation and reoccupation of the building, areas of powdering and flaking paint were anticipated and recorded. However, the overall stability of Marsh's rather odd and inherently fragile system of monumental painting within such poor ambient conditions militated against introduction of consolidants and fixatives that could prove destabilizing over time.[5] It was decided that Ethulose (ethylhydroxyethylcellulose) would be employed as the fixative. Although Ethulose is a modern synthetic product, it shares many properties and is compatible with traditional materials. An aqueous solution ranging from 1% to 1.5% in deionized water and ethanol 1:1 was applied by spraying. Moreover, like the highly diluted rabbit-skin glue used to treat the Portinari mural, Ethulose did not alter the optical quality of the colors.

Conclusions

Tempera mural paintings that share many technical similarities with those of the Silk Road exist throughout the world. Two principal conclusions are drawn from the case histories discussed in this paper. First, although inherently fragile and sensitive to the environment, mural paintings executed in tempera media can remain stable over centuries, especially when protected from human intervention. Second, many problems of conservation can be treated effectively with minimal intervention, which avoids the introduction of potentially incompatible modern materials that change the character of the mural painting forever and may well prove deleterious over time.

Acknowledgments

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Notes

1 CM Bond M-1 PVA emulsion (see Materials and Suppliers) was used in a 20% dilution.

2 Gore-Tex (see Materials and Suppliers) is a polytetrafluoroethylene (PTFE) in sheet form. It has an unusual semipermeable nature that allows transmission of aqueous and nonaqueous liquids and vapors, while being inert and incapable of adhering to other materials.

3 In this case, the relative success of removal was determined by examining cross sections of the mural painting before and after treatment at 200× magnification. Before treatment, layers of shellac fluoresced conspicuously orange on and below the painted surface of the mural. After treatment, a very thin layer of orange fluorescence was visible just below the painted surface.

4 The analyses were carried out by the Conservation Science Department, National Gallery of Art, Washington, D.C. The conservation treatment was carried out by Christy Cunningham-Adams. Unpublished reports on this mural and its conservation are located in the Archives of the Architect of the Capitol, Washington, D.C.

5 The U.S. Custom House is under the jurisdiction of the General Services Administration. The project development was carried out by the author (for Preservar, Inc.), and the conservation treatment by Perry Huston and Associates and New York Conservation Associates. Scientific analyses were carried out by SciCom, Inc., Professor Richard Wolbers (University of Delaware), and Professor Frank Matero (University of Pennsylvania).

Materials and Suppliers

CM Bond M-1 PVA emulsion, Conservation Materials, Ltd., 1165 Marietta Way, P.O. Box 2884, Sparks, NV 89431.

Ethulose, Berol Noble Inc., Meritt 8 Corporate Park, 99 Hawley Lane, Stratford, CT 06497.

Gore-Tex, Gore, Inc., 555 Papermill Road, Newark, DE 91714-9329.

Rhoplex AC-33, Conservation Materials, Ltd. (manufactured by Rohm and Haas Company, Philadelphia, PA).

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KEYNOTE ADDRESS

Geotechnical Issues in the Conservation of Sites

Robert E. Englekirk

The forces of nature have been reshaping our planet for millions of years. Humankind has been reasonably successful, at least locally, in attempts to control the impact of this process where a concerted effort can result in a decided benefit. The cost and effectiveness of constraining natural geotechnical processes are important considerations in the development of new structures, since permanent solutions may not be possible regardless of cost. Time and cost are also of concern in efforts to preserve ancient grottoes; an added factor here, however, is the impact of the control methodology on aesthetics. Accordingly, the objective becomes the appropriate balance between effectiveness, cost, and aesthetics.

What constitutes a "balanced" program will not be decided by the geotechnical consultant. Accordingly, those involved in the decision-making process must understand the geotechnical issues at hand and the mitigation alternatives available, which together are the focus of this chapter.

Geotechnical Issues

Site soils and geology are fundamental to every grotto preservation effort. Two problems are exclusively geotechnical in nature: deterioration of the grotto structure and water intrusion. The grottoes at Dunhuang and Yungang in China are cases in point.

Geological instability of grotto structure

Excavated caves such as those at Dunhuang and Yungang were created in relatively soft sandstone deposits, which allowed easy excavation but whose surface is easily eroded by water or wind. Sandstones form when sand is consolidated under uniform triaxial pressure, typically in a marine environment. Pressure, or the removal of pressure, is a major consideration in the deterioration of grotto structures, as the face of a sandstone cliff is subjected to pressure on all sides except for the exposed cliff face. This lack of surficial pressure causes the compacted sandstone to expand laterally in the direction of the cliff face, thereby promoting surficial

delamination and/or the creation of weakened planes parallel to, but behind, the cliff face. Once a weakened plane has been created, it is soon further weakened by the intrusion of water until a block is formed. Surficial erosion and cliff recession are caused by these two related events, generally identified as surface deterioration and block failure. The rate of cliff recession, though not uniform, given the episodic occurrence of block failure, is fairly predictable. At the Mogao grottoes near Dunhuang, a reasonable estimate of this rate is about 1 cm per year based on an observed rate over the last twelve hundred years. Anomalies, either extant or introduced, can significantly accelerate the process. This will depend to a large extent on the nature and amount of the erosion, whether by wind and sand abrasion or by water. Consequently, any cliff recession abatement program must strive to (a) restore lateral pressure and thereby maintain the internal integrity of the sandstone formation, and (b) reduce the impact of abrasives on the surface of the cliff.

At the Mogao grottoes, the surficial deterioration is largely the result of wind and sand abrasion and clearly illustrates how a historically predictable rate of cliff recession can accelerate when uncontrolled. Understanding the deteriorative process at Dunhuang also suggests how it may be most effectively controlled. Sand deposits (dunes) above and behind the cliff face are continually being moved by the wind down the back slope above and over the cliff face itself. This action is, at least in part, responsible for the cliff's uniform recession. Accelerated erosion has occurred near the main site. Here, an anomaly has caused the sand flow to concentrate over a grotto, collapsing the grotto roof and creating an over-recessed condition. Well-intended attempts to control or eliminate surficial delamination have been undertaken in the past. The placement of a Ming-period pagoda and construction of a rock facing in the 1950s have succeeded in eliminating the recession of the cliff face at those locations. These remedies, however, have not stopped the recession of the back slope; and this recession has tended to channel the sand flow, causing accelerated erosion to areas where the cliff face mediation has not been undertaken. Attempts have also been made to control the rate of deterioration of the back slope by covering it with a cementitious material. These interventions have been entirely ineffective, however, because the hardened surface has broken down, allowing slabs of cemented sand to slide down the back slope.

The cliff face at Yungang has also receded. Here the recession is wind- and water-related, and block failures appear to have been common. Ming-epoch interventions to control cliff recession have been, and should continue to be, more effective than at Dunhuang, because the amount and effect of abrasive agents flowing over the adjoining cliff face at Yungang appear to be less than at Dunhuang.

Water intrusion

Grottoes located in regions where rainfall is considerable and groundwater tables are likely to fluctuate will experience variations in the moisture con-

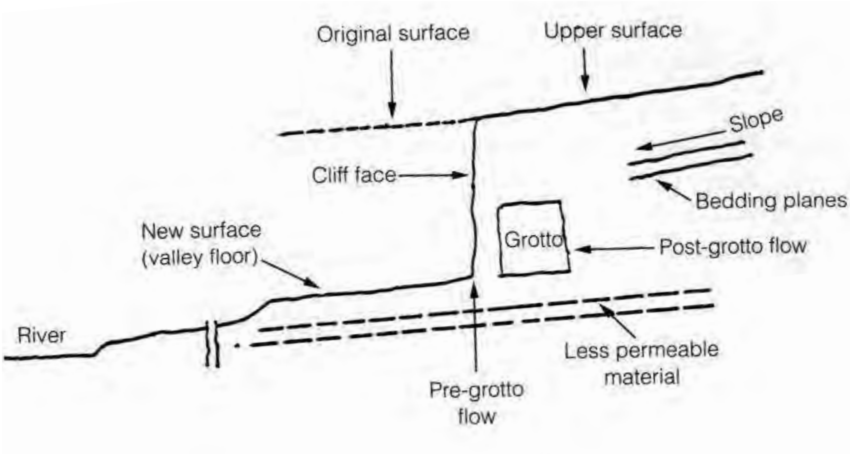


Figure 1
Schematic cross section through the cliff face at Yungang.

tent of the rock that constitute the grotto structure. At Yungang, water reportedly flows from the base of grotto walls during the rainy season. The natural geotechnical process that originally formed the cliff site selected for grotto excavation is both the main source of the problem and a resource for possible solutions.

A sandstone cliff face, as shown in cross section in Figure 1, is usually created by the formation of a river valley. Water will flow through the ground in the direction of the valley floor, especially if the bedding planes slope in that direction. The toe of the cliff will usually coincide with a change in the character of the sedimentary material near the valley floor, which is often less permeable than that of the cliff face. Water will descend to this less permeable stratum and then flow toward the river valley. Before the grotto was excavated, water would, because of the change in overburden pressure, tend to flow out at the intersection of the valley floor and the cliff face, contributing significantly to its recession. With the excavation of the grotto and the associated change in overburden soil pressure inside the grotto, the water intrusion point moved back to the intersection of the grotto floor and wall.

Understanding this water-flow pattern suggests two mitigation strategies: (1) remove or reduce the source of underground water, and/or (2) install an intercept that provides an alternative escape path for the subsurface water.

Alternatives for Cliff Recession Abatement

Cliff recession at Dunhuang

Cliff recession at Dunhuang is caused almost entirely by the abrasive flow of sand over the surface of the cliff face and back slope. The effectiveness of any abatement effort will depend on the quantity of abrasives it must resist. Accordingly, wind-tunnel studies and field experimentation directed toward reducing the flow of the sand should be pursued.

Surficial cliff protection alternatives should be installed when the experienced "average" recession rate cannot be tolerated for long or when accelerated recession is occurring or might reasonably be anticipated.

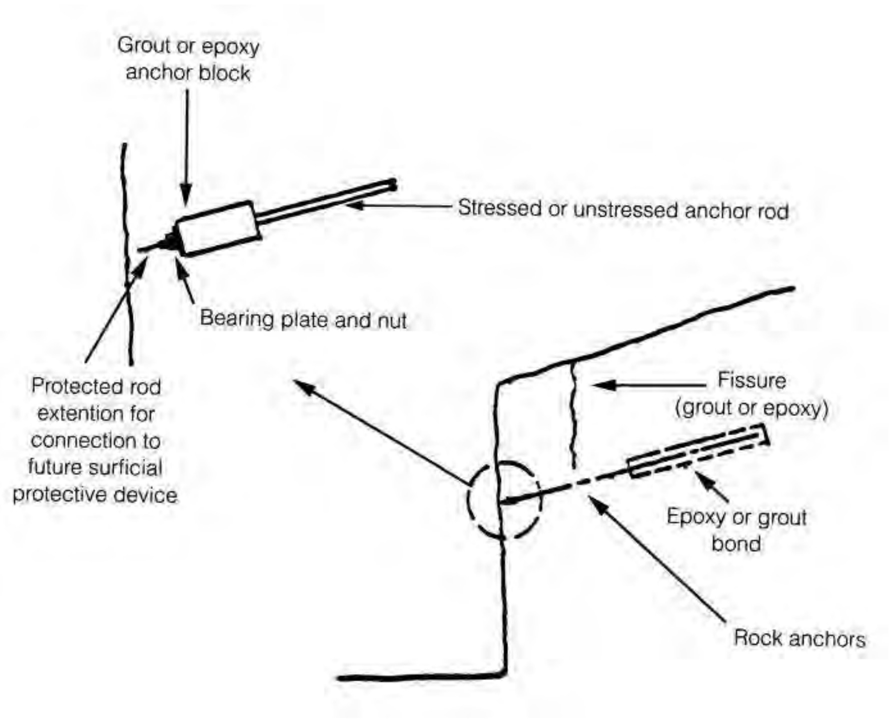


Figure 2
Rock bolting a fissured cliff face.

Where cliff recession rates can be tolerated but block failures seem likely, mitigation measures may be undertaken. Rock bolting, in conjunction with crack or fissure repair, may proceed in anticipation of the future addition of a surficial cliff-protection device. One means of accomplishing this staged abatement process is described in Figure 2.

Any slope or cliff face will recede if entirely unprotected. When a slope, such as the back slope at Dunhuang, is uniform, the rate of recession may be tolerable if the flow of abrasive agents over the surface is minimized. Cohesionless material will tend to erode unevenly, even on a regular slope, and this tendency will increase as surface irregularities develop.

Erosion control of otherwise stable slopes is a problem commonly encountered in highway construction, especially in areas where rainfall is heavy. Durability, cost-effectiveness, and maintainability are the principle variables with which abatement alternatives are measured. In many cases, the surfaces of stable slopes are irregular, as they are at Mogao, and this irregularity impacts the cost and effectiveness of erosion-control devices. Surficial back-slope treatments should be attempted at Dunhuang. Back-slope stabilization will not be easily accomplished here because the back slope contains topographic irregularities that will make the development of a uniform mitigation methodology difficult.

Slope erosion control devices may be broadly categorized according to the following objectives:

1. limiting the impact of erosive agents;
2. protecting or isolating the surface material with a covering device; and

Figure 3
Erosion control by controlled-velocity vertical channels and gradual swales at the Getty Center, Los Angeles.

3. improving the ability of the surface material to resist erosive agents.

Usually only one of these approaches is adopted and applied. At Dunhuang, the most effective solution will probably be to combine all three. Before describing how these methodologies might be effectively combined, the following summarizes the usual implementation of each method and its effectiveness.

Limiting the impact of the erosive agent is the method most commonly used to control erosion by water, since water will not significantly erode a surface if both the quantity flowing over the surface and the velocity of flow are controlled. This is accomplished by reducing the slope length and steepness and increasing its roughness. Time-tested methods include terracing and roughening the surface by plowing it across the slope. Channeling the flow of the erosive material is also a commonly adopted methodology. The construction of channels controls the velocity, direction, and location of flow. The introduction of gradual swales and controlled-velocity vertical channels is shown in Figure 3. Clearly, the aesthetic impact is significant. Swales and channels must be continuously maintained, as the concentrated flow, if allowed to deviate from protected paths, will cause local failures that may be of significant proportion. Treatment between swales, usually vegetation, must also be maintained in a manner consistent with the mitigation program.

Protecting or isolating the surface material from the erosive agent by installing a layer of concrete is a method commonly used to protect highways in Japan. The basic features of this technique include rock bolts that extend through loose surficial deposits and are anchored into firmer substrata; a mat of ferrous reinforcement placed over the surface material; and, finally, concrete applied over the existing surface. An appropriately designed and installed application, if maintained, should virtually eliminate longevity concerns. Unfortunately, concrete is not easily applied to difficult surfaces and volume changes in the material itself will cause cracks to form, especially where the surface is irregular and material thickness is not uniform. Cracks will allow water to penetrate, causing the reinforcement to rust and creating flow channels or piping in foundation material below the concrete. Thus, the protective device may itself become a significant problem. For example, the installation of a reinforced concrete surficial device at the Yulin grottoes near Anxi was in progress in 1991, and some of the difficulties described above are apparent in Figure 4. Given the extremely irregular nature of the exposed cliff face at Yulin, this type of surface protection is probably the appropriate solution, but its maintenance will undoubtedly be a problem.

Figure 4
Steel reinforcing laid on the surface in preparation for application of surficial concrete as an erosion-control measure, Yulin grottoes.

Improving the ability of the surface material to resist erosion is another alternative. *Bare-earth* erosion control is most frequently used on oversteepened construction slopes. The process involves spraying the exposed surface with a chemical, such as potassium silicate, that will bind the particles. The procedure is most effective in cohesionless materials such as sand, which is easily penetrated and readily absorbs a fluid. The

aesthetic advantages over the previously described alternatives are obvious, as is the impact on cost. Longevity then becomes the issue, which may be significantly improved in the design of a program that minimizes the impact of secondary actions, and through the introduction of nonmetallic fiber reinforcement. Periodic retreatment of the surface must take place, or the resulting problem may be worse than the original one.

The erosion of the back slope at Dunhuang is probably best controlled by integrating a bare-earth treatment with localized enhancements, provided topographic irregularities and anomalies—such as excavated grottoes—are considered and carefully incorporated into the program. The development of a bare-earth treatment program must consider how maintenance is accomplished and recognize that any surface hardening is likely to create a weakened plane below the zone of hardened material, which may result in a slide. These two considerations can be included in a general solution that maintains the aesthetics of the slope. The tendency of the hardened material to slide can be controlled by the introduction of either horizontal or vertical channels that are rock bolted into the firm underlying sandstone strata. These reinforced areas can then be tied to the surface strata by introducing nonferrous fiber reinforcement into the upper sands before the bare-earth treatment is applied. Reinforced areas should also provide access for construction and maintenance.

The treatment of anomalies will undoubtedly require a combination of solution methodologies. One example is the condition that now exists at caves 272 and 460. A cross section through this portion of the cliff (Fig. 5) graphically illustrates the problems. Major issues that must be addressed by any solution include the cracking and differential settlement in the roof of Cave 272, the expanding hole in the roof of Cave 460, and the accelerated erosion caused by the "river of sand" flowing over Cave 460.

The elements of the solution illustrated in Figure 5 include

- the reinforcement of the cliff face by the installation of reinforced concrete buttresses;
- the installation of upward-sloping rock anchors, which secure the buttresses to the grotto facade and relieve the vertical load imposed on the roof of Cave 272;
- the integration of a new concrete roof structure supported by the grotto walls and new buttresses supporting the existing grotto roof structure; and
- the integration of reinforced concrete sand-diversion channels into the surficial treatment above the grottoes in the back slope; an alternative here would be a gunite-reinforced surface applied locally.

Cliff recession at Yungang

The cliff recession at the Yungang grottoes appears to be almost exclusively attributable to block failure. The average rate of recession appears to be

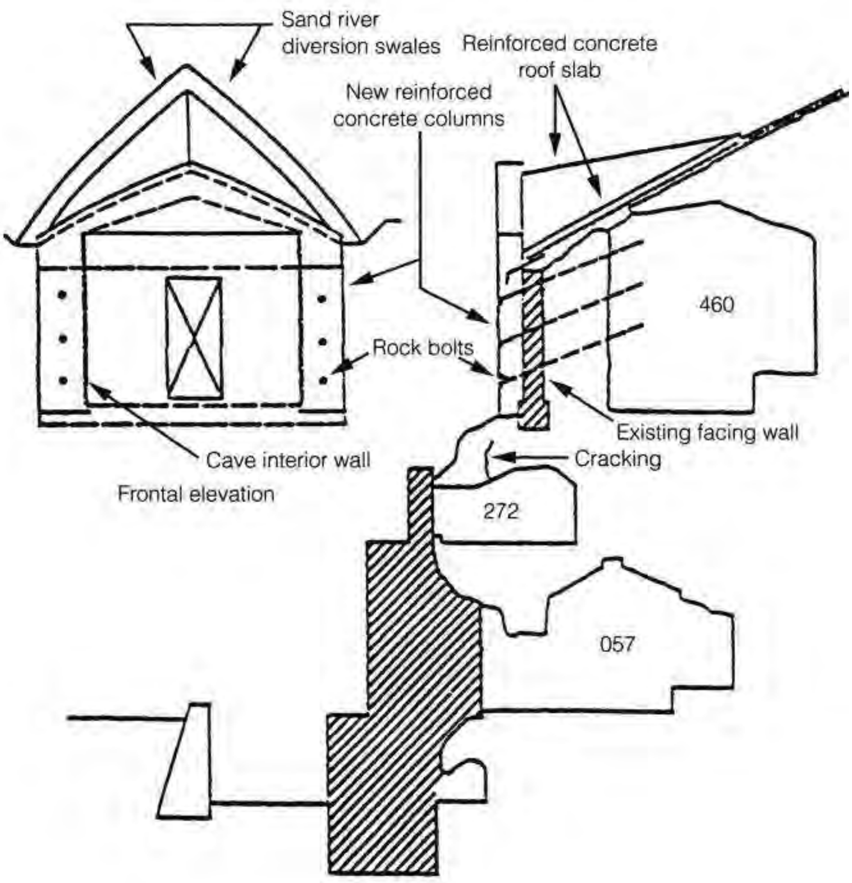


Figure 5
Cross section of Caves 272 and 460 at Mogao.

about the same as at Dunhuang, although the rate is not regular. Block failures may be prevented by anchoring the separating block to the base material with rock anchors, as shown in Figure 2. At Yungang, fissure propagation is more rapid than at Dunhuang because rainfall is greater and the surface of the grotto roof tends to drain toward the cliff face. The effectiveness of any rock-anchoring procedure will require a thorough fissure-repair program and may be enhanced by a diversion of the surficial water flow above the grottoes.

Cave 19 at Yungang poses a special problem of cliff face delamination, as the roof over the grotto does not appear to be thick enough to safely accept rock anchors. Figure 6 shows a section of what remains of Cave 19, once the inner chamber of the original shrine. The antechamber no longer exists, as it was the victim of successive surficial block failures. Figure 7 shows an elevation of the extant exterior wall of Cave 19. The left side window once contained two smaller windows similar to those that still exist on the right side. Clearly, the structural deterioration of the facade is in immediate need of abatement. A physical enclosure of the grotto has been proposed, the primary intent being to control pollutant intrusion via fabric filters. The strengthening described in Figures 6 and 7 may be integrated into the facade development. The two major elements of the strengthening program are the provision of a vertical support for the grotto roof over the left window and the construction of a horizontal truss within the roof enclosure. The latter will provide lateral support for

Figure 6
Vertical section of Cave 19 at Yungang grottoes.

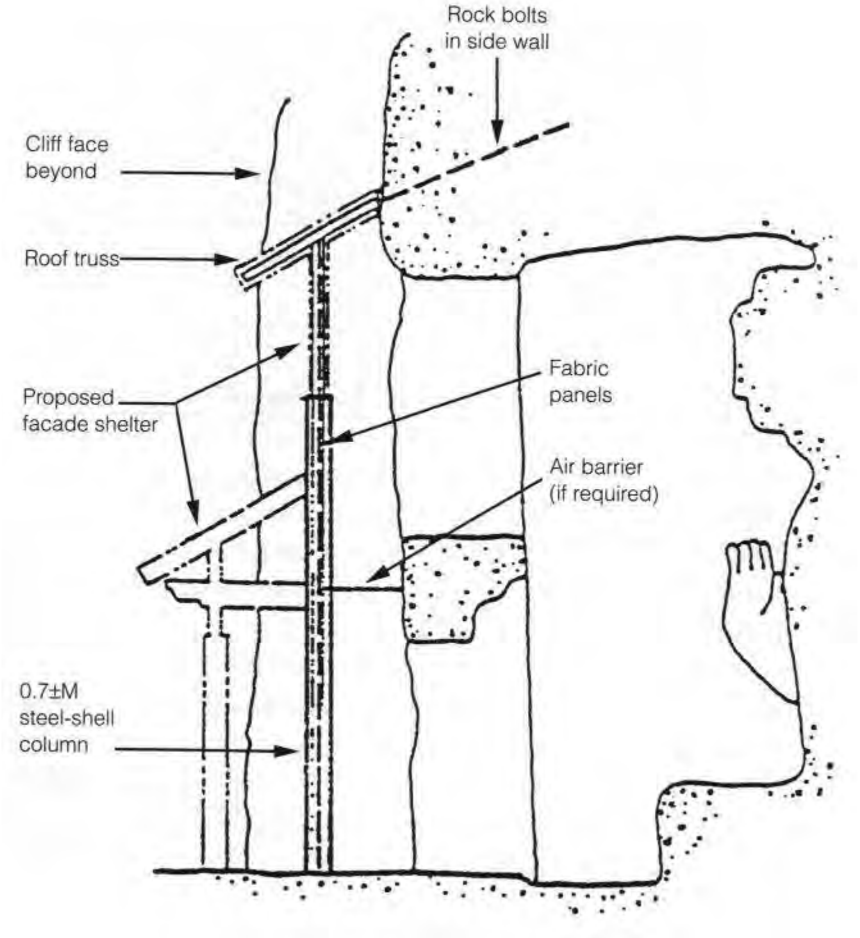
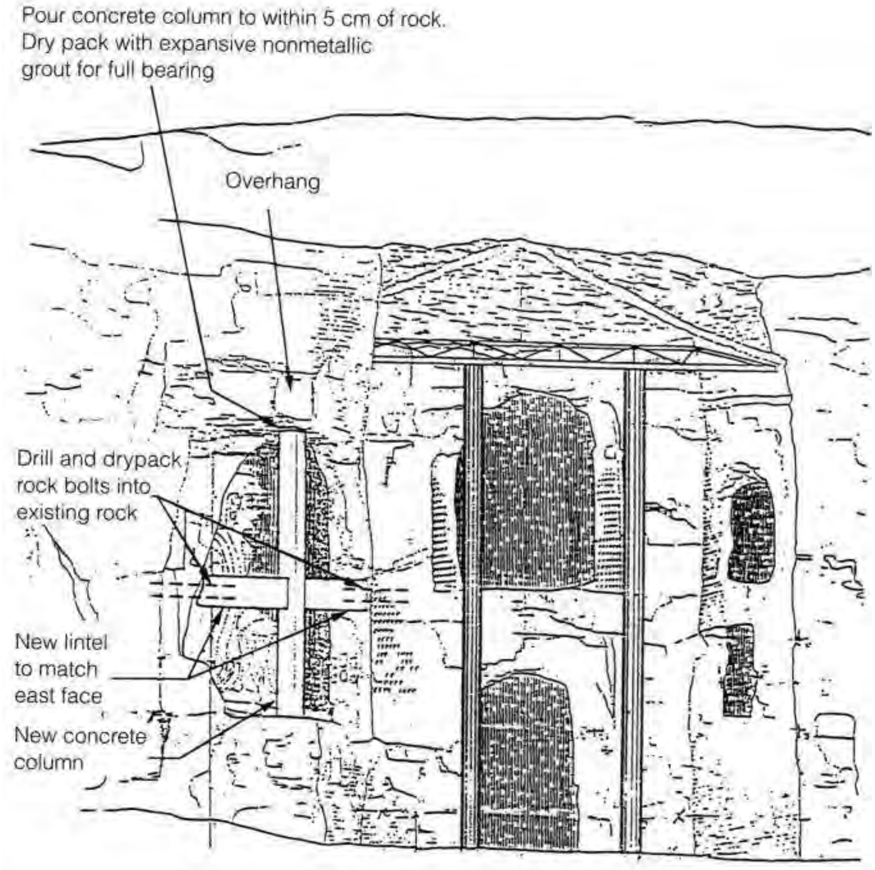


Figure 7
Frontal elevation of the extant exterior wall of Cave 19, Yungang.



the sandstone fascia over the door, allowing it to be anchored into the side walls of the grotto instead of the fragile roof of the grotto itself. The only constraints to the aesthetic objectives of this strengthening strategy will be the need to provide vertical support for the overhanging ledge at the left window and the provision of lateral support to the blocks of sandstone over the grotto entrance at the roof line. The latter support must be high enough to reach competent material that can be penetrated with confidence on either side of the grotto.

Planning for Erosion Abatement

Effective erosion-control programs at Mogao and Yungang and other grotto sites will require a significant effort in terms of engineering as well as cost. A variety of solutions do exist, however. Alternatives should be planned to the extent that feasibility is ensured and aesthetic impact and cost may be assessed. This accomplished, the most reasonable program will usually become clear. Creativity on the part of the conservator, engineer, and builder is essential. Easy solutions and "quick fixes" will often create more problems than they solve.

Water-Intrusion Abatement

Water mitigation at Yungang

Two mitigation measures have previously been identified: source reduction and flow interception. The amount of water that reaches an aquifer or water-bearing strata is a function of the permeability of the material overlying the aquifer and the extent to which water is allowed to accumulate on the surface. Source-reduction objectives must then typically focus on improving the surficial flow of water that would otherwise reach the aquifer and, where necessary, introducing an impermeable barrier.

Surficial flow can be improved by grading and the installation of drainage swales. This objective is contrary to that associated with erosion control, since the velocity of the surficial water must be maintained to minimize the rate of absorption. The appropriate slope will be a function of the soil characteristics and ground cover. Where the slope is not sufficient, concrete or a less permeable channel must be created to rapidly convey most of the water to the valley floor, thereby reducing the amount of water that will flow through the aquifer.

The permeable characteristics of the surficial soils can be altered chemically or through the introduction of geotechnical products such as geodrain or geomat. These are generic names for a particular type of subsurface drain and an impervious polymer sheet, respectively, which create a barrier and reduce the velocity of flow that might otherwise be required to effectively remove the water at the surface. Geodrain is a fabric that captures and channels water to an included pipe, while geomat is essentially an impermeable barrier. The various approaches to improving surficial flow can be combined as shown in Figures 8 and 9. Before localized drainage solutions such as these are attempted, site geology and hydrology characteristics must be studied to ensure that the source of water reaching the aquifer has been identified.

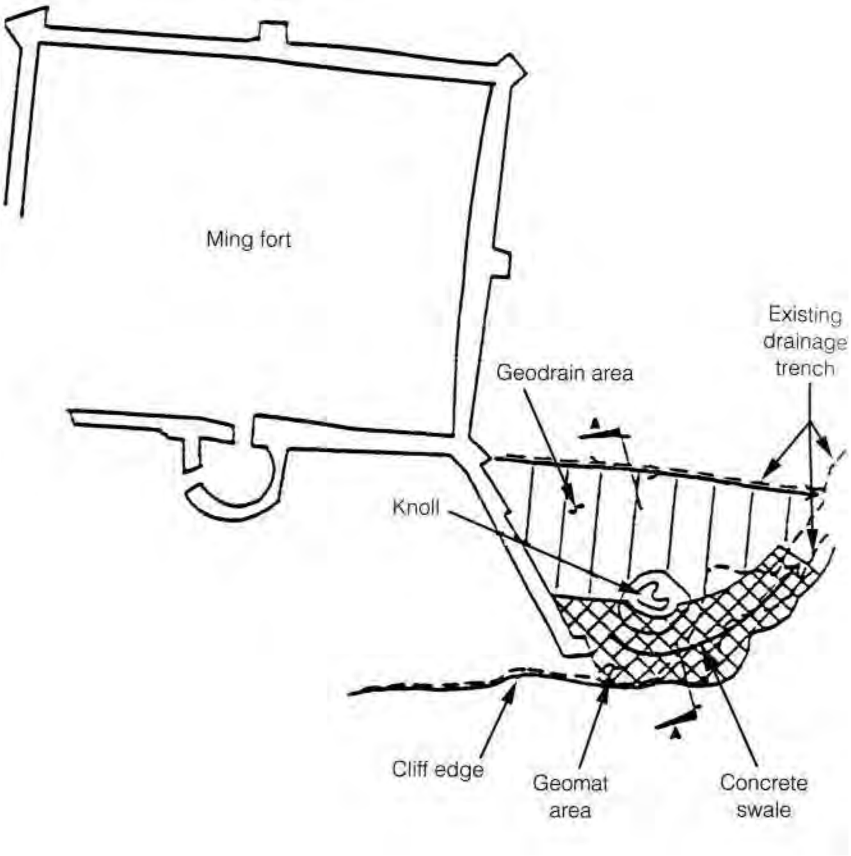


Figure 8
Plan of proposed surface drainage-control system, Yungang.

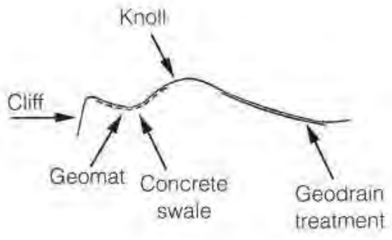


Figure 9
Schematic section of a proposed drainage-control system, Yungang.

Water interception can be an effective means of diverting the flow of underground water. This procedure involves the construction of a major access tunnel or tunnels from which a peripheral drainage system may be constructed. The major access tunnel usually serves as the drainage channel, collecting water from the peripheral tubes and discharging the flow beyond the area of concern. Advantages associated with a water-interception program include the ability to more accurately locate the aquifer and alter the intercept field until the objectionable flow has been eliminated. The conceptual development of a water-interception program is described in Figure 10, with a typical detail connection of a collector tunnel shown in Figure 11.

Planning for water mitigation

In general, source reduction will, if effectively accomplished, reduce the level of moisture experienced in the grotto walls as well as eliminate the water flow into the grotto. The major drawback is the difficulty associated with identifying the source of the water supply to the aquifer. If site geology and hydrology are complex, it is unlikely that the source of water to the aquifer will be sufficiently reduced by surficial treatments. Water interception, on the other hand, allows for an accurate location of the aquifer and its effective control. An effective, peripheral drainage system will rely on pressure relief much the same way as the subterranean flow was initially attracted to the grotto (Fig. 1). Accordingly, it may be impossible to

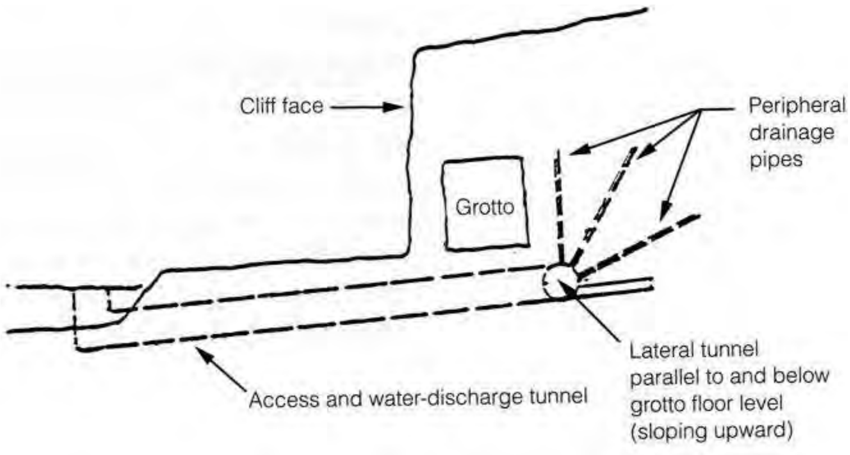


Figure 10
Schematic section of a conceptual water-inception system for Yungang.

control moisture occurring at the wall of the grotto since the grotto will, in effect, remain a pressure relief tube.

Each mitigation system has proved effective, depending on site characteristics. Site geology and hydrology are typically complex, especially in sedimentary formations. The drainage, or source-control, system illustrated in Figures 8 and 9 appears to have a reasonable chance of success. Its

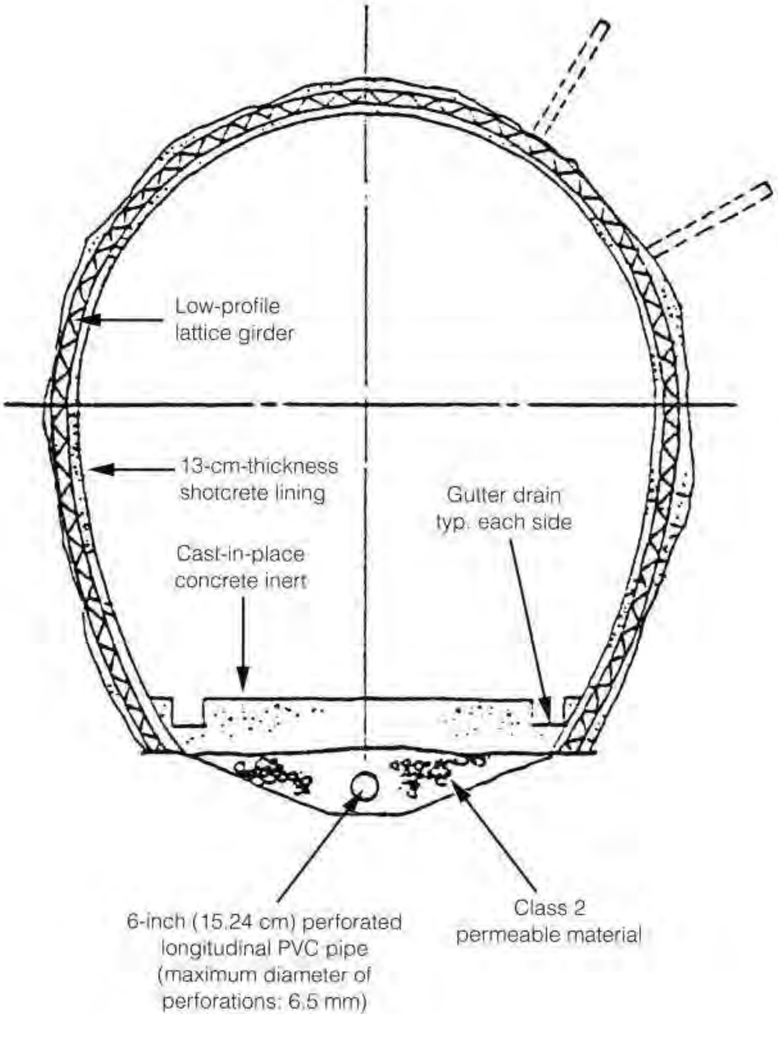


Figure 11
Typical water-interception system used in tunnels.

installation should reduce the amount of water from the source. The overall effectiveness of any surficial drainage program will be determined only by observing and monitoring the level of subsurface water before and after the installation of surficial flow control devices. Similarly, the grottoes north and west along the cliff face seem to afford an opportunity to experiment with intrusion-abatement programs. Clearly, water intrusion must be abated if the grotto contents are to be preserved. For an appropriate solution to be developed, knowledge and experience must be effectively combined with experimentation.

Review of Stabilization Projects at the Mogao Grottoes

Sun Rujian

The decision to undertake stabilization of the Mogao grottoes was made by the Ministry of Culture in the autumn of 1962. On 20 November of that year, the Ministry sent a document to the Cultural Bureau of Gansu Province, noting that "with regard to the project for stabilization of the rock of the cliff, the Ministry of Culture has already reported to the Premier and applied for funds and materials. Design and construction are to be the responsibility of units designated by the Ministry of Railways." Geological study, survey, and mapping began in November– December 1962.[1] Discussions of the stabilization plan and construction design took place in the spring and summer of 1963, and the construction team arrived at the Mogao grottoes site in June to begin the stabilization project.[2] In July 1966, after three years of construction work, the project was essentially completed. A length of 576.12 m of cliff face and 358 caves were stabilized or reinforced.

The first and second phases of the three-phase project had as primary objective the stabilization of the grottoes. The third phase was mainly devoted to building walkways outside the grottoes, integrating the first two phases of the project. Through a series of activities—beginning with experimental stabilization of the northern and southern sides of Cave 254 in the 1950s and ending with the completion of a fourth phase of the project in the 1980s—the danger of geological deterioration of the grottoes and related issues of visitor safety have been largely eliminated.

Basic Causes of Deterioration

The Mogao grottoes were excavated in the steep cliffs on the western side of Daquan River. The site is 1,680 m long and 20–25 m high and was excavated out of the Jiuquan stratum of the Quaternary period—a stratum composed of conglomerate, gravel, and sand, poorly consolidated with a little calcareous cementation. The Dunhuang region is characterized by lack of humidity and rain, great diurnal temperature differences, and the tendency of the rock formations to weather easily. On the national classification of seismic intensity zones, Dunhuang is a degree 6 seismic region. According to seismic records, seven earthquakes occurred between

1927 and 1960. Although they were not high on the Richter scale, they were of high frequency and were damaging to grottoes that had been excavated in close proximity to one another and in which there were rock fractures.

Deterioration of the Mogao grottoes is caused by a combination of environmental, geological, and human factors, as discussed in the following sections.

Cracks parallel to the cliff face

Cracks parallel to the cliff face and generally perpendicular to the ground pose a significant threat to the grottoes. The cliff was formed by action of the river cutting downward through the soft sediments. As the cliff formed, its outer face became a stress-release region, and cracks gradually developed parallel to the face. Excavation of the grottoes further weakened the rock, reducing stability and resulting in widening of the cracks. Under the combined action of the cliff's own weight and external forces, partial and strip collapses have occurred many times over the course of time. In an initial survey, twenty-three cracks and crevices were found in 157 caves on various levels in a 160 m section, from Caves 21 to 59. Cracks were mainly located on the third and fourth levels, and cut through 90 caves. Crack 13, between Caves 442 and 434, was 45 m long. On the basis of long-term observations, there were signs that this crack had grown larger before stabilization.[3] Caves 289 and 290 on the second level; Caves 435, 436, and 438–442 on the third level; and the antechambers and main chambers of Caves 446 and 448 on the fourth level—all within the range of this crack—collapsed about a thousand years ago (Figs. 1, 2). Clearly, the existence and growth of crack 13 has constituted a serious danger to the safety of the grottoes within this section (Fig. 3). There are many other places in the caves where conditions are similar. Therefore, this is a form of deterioration in the grottoes to which special attention must be given in all stabilization projects.

Cracks perpendicular to the cliff face

Structural crevices are generally perpendicular to both the ground and the cliff face and may have developed from bedrock joints. They occur at 5–20 m intervals. The orientation of the cracks has a relatively consistent pattern of direction, from the first- and second-level caves to the top of the bedrock and extending 2–9 m into the caves. Although they do not have as severe an effect on grotto safety as do edge crevices, they crosscut the bedrock and can cause large-scale grotto collapse if they happen to be present in the same area as the parallel cracks.

Other cracks

In addition to the two types of cracks already described, other vertical and horizontal cracks are found on the cliff faces. Vertical cracks are, for the

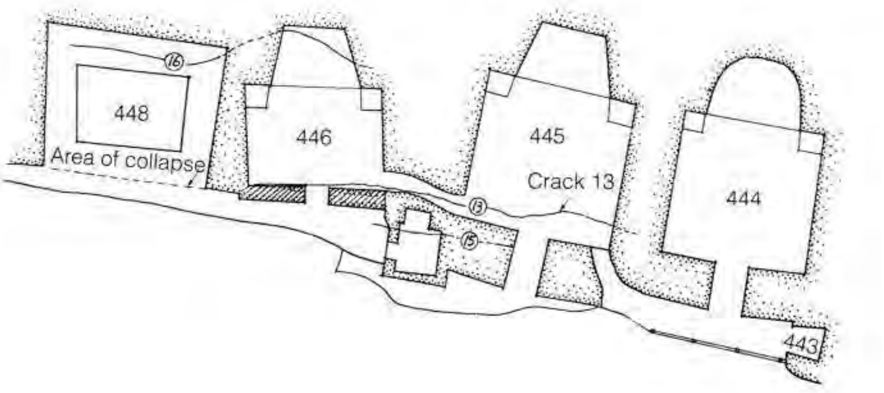


Figure 1
The front part of Caves 446 and 448, fourth level, section 3, collapsed along crack 13. The front adobe wall of Cave 446 was built in the Song dynasty. About 20 m on that level are affected by this crevice.

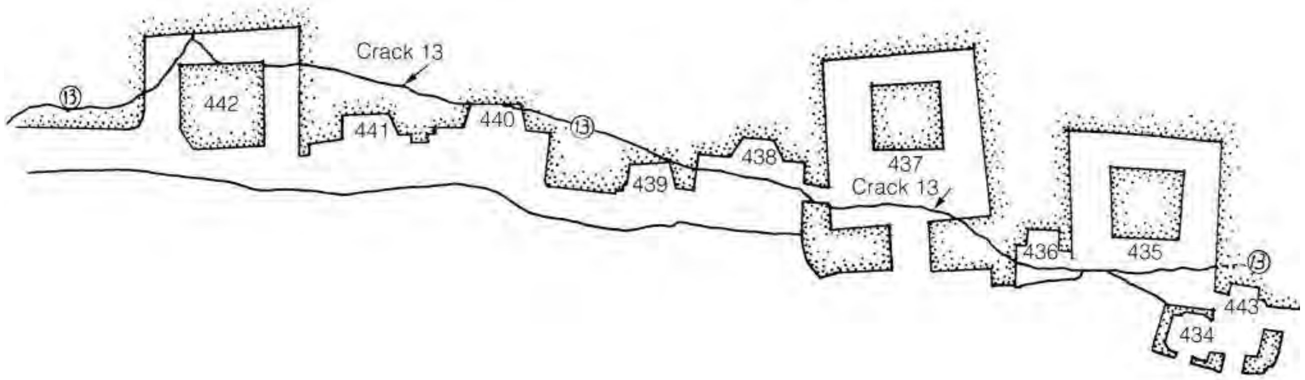


Figure 2
The front part of five caves (third level, section 3), with wall paintings dating from the Five Dynasties period, has collapsed. About 40 m on this level are affected by crack 13.

most part, seen at the tops of antechambers and corridors and are not particularly obvious. They were formed as a result of stress generated at the tops of the caves after excavation. Small-scale rock flaking readily occurs along the cracks. Horizontal cracks are produced by weathering and erosion of the thin layers of fine sand interspersed between the gravel layers.

Overhanging cliffs and unstable rocks

Resulting from the development of the types of cracks described here and the bedrock collapses, many unstable rock masses have been left overhanging the cliff faces. For example, there is a 55–65° negative slope of overhanging and fragmented upper bedrock above Caves 401, 402, 202–205,

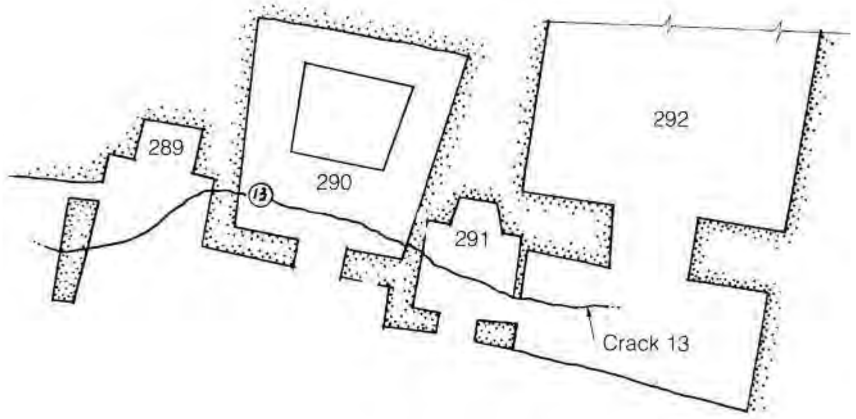


Figure 3
Second-level caves in section 3. About 15 m are affected by crack 13.

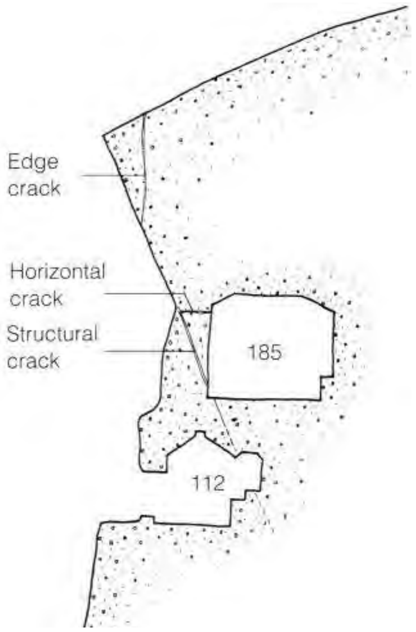


Figure 4, above
Section showing cracks of many types in the same vicinity.

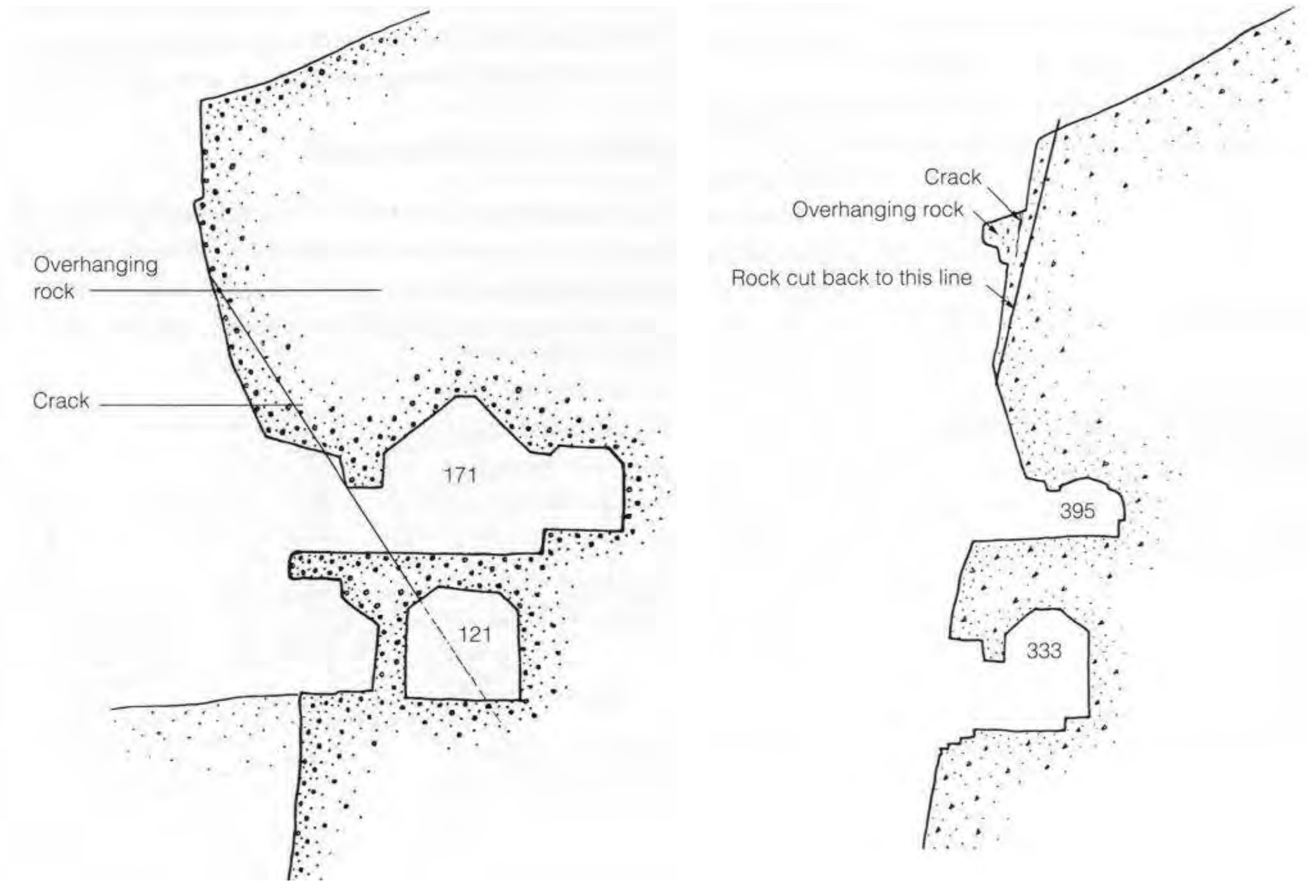
Figure 5, below
Sections showing suspended rock masses and cracks, and reduction of dangerous overhangs by cutting back the rock face.

and 170–172. The rock edges of Caves 328–365 have been eroded over a long period by wind-driven sand and occasional rain. This has left many isolated overhanging rock masses; these subsequently disintegrate due to the moisture from rain and snow, and shed material that falls down the cliff (Figs. 4, 5).

Deterioration caused by human factors

The Mogao grottoes were constructed from around 400 C.E. to the latter part of the ninth century. Over this period of time, the cliff face, which is more than 900 m long in the southern part of the site, comprised a virtual honeycomb of caves. According to records of the time, all available space for excavation of grottoes had already been used up by the late Tang dynasty.[4] In the region of early grotto construction, in the middle section of the southern area, three to four levels of caves are distributed across a sectional cliff 15–25 m high and 160 m long, from Caves 21 to 59. Of the early grottoes, these are in the best condition. There are 157 caves concentrated in this 2,500 m^2 cliff face, with one cave every 16 m^2, on average.

Altogether, there are 78 caves that represent the essence of the Tang grottoes. They are concentrated on a 2,100 m^2 area of cliff face, 140 m long, each cave averaging 27 m^2. Under such dense conditions, the middle and lower parts of the bedrock have been hollowed out, depriving the upper rock of firm support and creating conditions of instability. Moreover, the small grottoes excavated between the large ones have further weakened the stability of the outer face of the bedrock.



Prior to the Sui dynasty, grottoes were usually excavated in the upper part of the bedrock, specifically on the second and third levels. In the Sui dynasty, small caves were formed between the antechambers of the grottoes that already existed, for there was very little space remaining on the cliff face itself (Figs. 1, 2). Several typical examples of these small caves include

- Cave 425 (Sui dynasty), excavated between Caves 423 and 424 (Sui dynasty);
- Cave 426 (Sui dynasty), inserted between the antechambers of Caves 424 and 427 (Sui dynasty); and
- Cave 430 (Northern Zhou dynasty), cut between the antechambers of Caves 428 and 431 (Northern Wei dynasty).

The formation of caves such as these often caused damage to surrounding structures. For example, two small Sui dynasty grottoes, Caves 433 and 434, were excavated between the antechambers of Caves 432 (Western Wei dynasty) and 435 (Northern Wei dynasty) (Fig. 3). After the small caves had been excavated, the wall thickness was only 10–30 cm, severely weakening the rocks between the caves. Similar damage was caused between grottoes produced on different levels, as in the case of Cave 292 (Sui dynasty), situated below Cave 435 (Northern Wei dynasty). Since the rock that serves as both the roof of Cave 292 and the floor of Cave 435 is rather thin, the floor in front of the central pillar in Cave 435 (on the northern side of Cave 436) collapsed under the pillar's weight. Similarly, Cave 44 (Tang dynasty)—the antechamber of which runs 6 m into the cliff face—was excavated beneath Cave 290 (Northern Zhou dynasty) and Cave 289 (Sui dynasty) to the south of it. The weight of the wall separating Caves 290 and 289 (60 cm thick) is concentrated on the middle portion of the roof plate of the antechamber of Cave 44, and the force produced by the load caused the collapse of the front parts of Caves 290 and 289 (Fig. 6a, b). There have been many similar cases. Some of the unstable factors resulting from grotto excavation have been located and resolved. However, some may not have been discovered yet, posing a hidden threat to the long-term survival of the grottoes.

Stabilization Measures

As early as 28 June 1954, the existence of various forms of damage and deterioration of the grottoes was pointed out by the Ministry of Culture in a letter to the Dunhuang Cultural Relics Institution:

> The most serious problem at the moment is that the grottoes themselves are in danger of collapsing due to geological causes and that the wall paintings and statues are being constantly eroded by wind, sand, snow, and water. Therefore, it is necessary to keep up our good efforts in the preservation and repair work.

The government departments responsible for cultural relics were required to reinforce the grottoes, to eliminate the threats to the grottoes

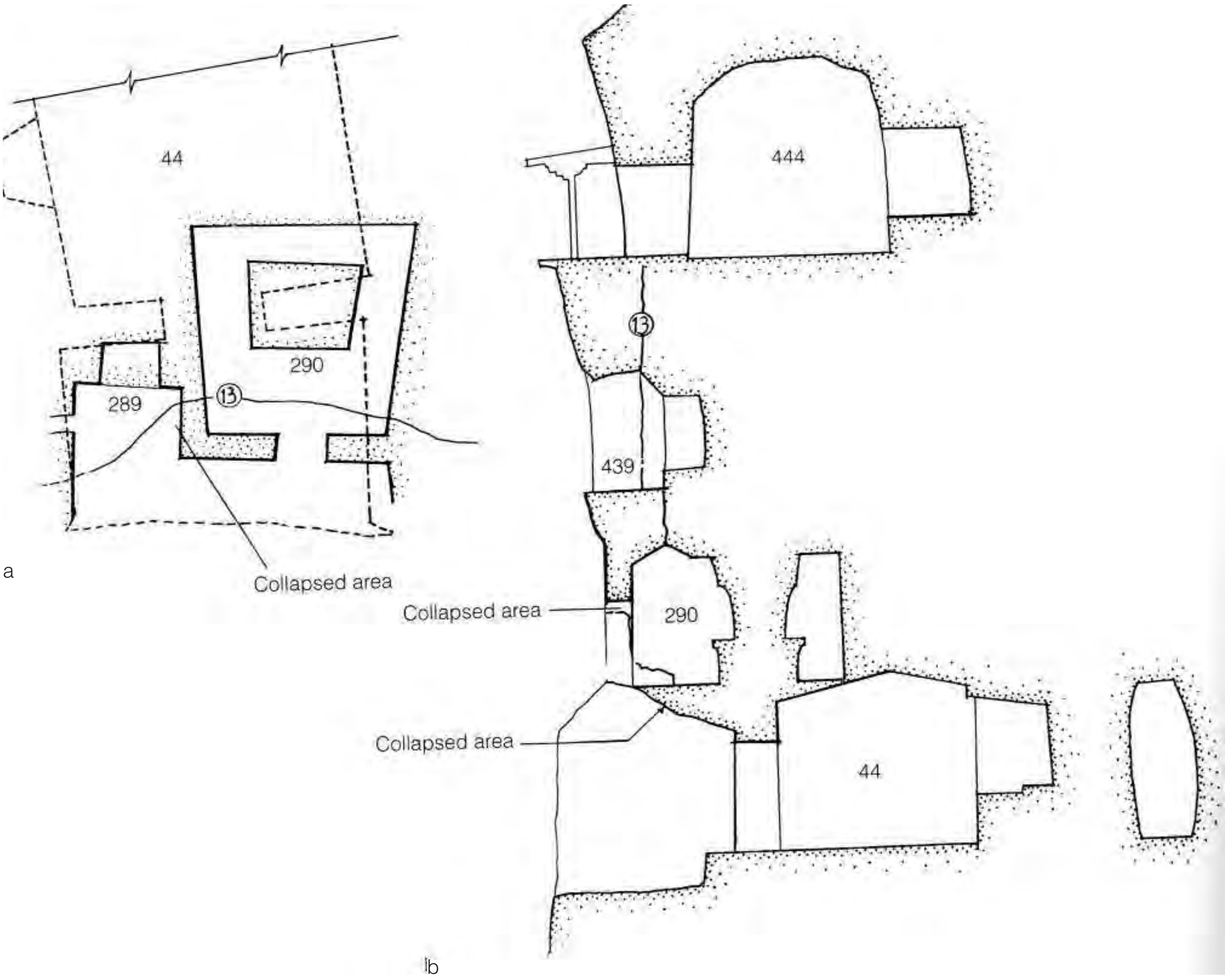


Figure 6a, b
Plan (a) and cross section (b) showing the relationship between deterioration of Cave 44 and Caves 289 and 290. The wall separating Caves 289 and 290 fell onto the roof of the anteroom of Cave 44, collapsing the left side of Cave 289 and the front part of the right side of Cave 290. Cave 44 was created during the Tang dynasty, with a span of nearly 8 m and a depth of 5 m. The excavation of this cave caused the front part of Caves 289 and 290 to collapse.

caused by deterioration, and to preserve the original style and features of the grottoes as far as possible. Many discussions were carried out in the spring and summer of 1963, and programs were proposed based on existing construction technology and on the patterns of occurrence and development of deterioration in the grottoes. Several of these technological measures are as follows:

Roof support

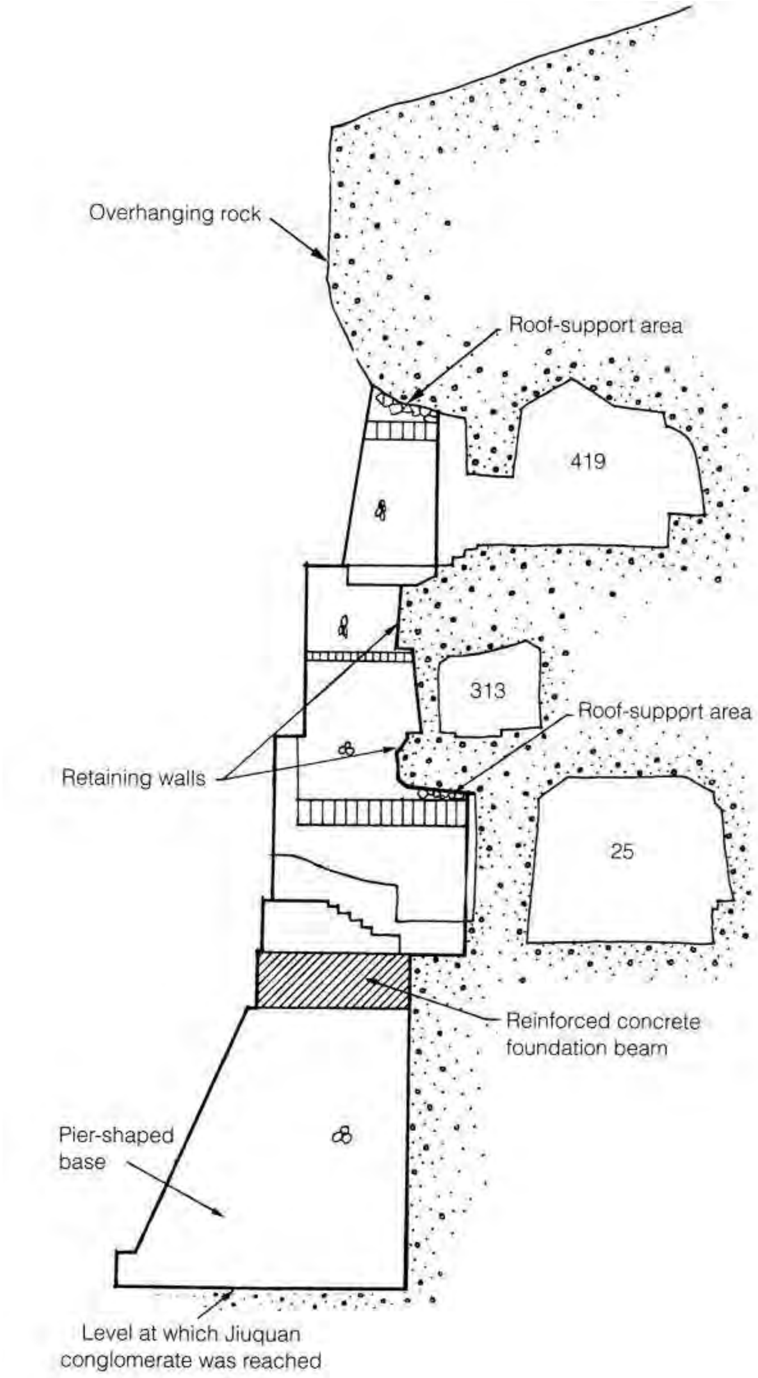
Since most Mogao grotto antechambers are open on one side, each antechamber roof is supported on only three sides by bedrock, and the front roof section is in a state of virtual suspension. If the antechamber has a wide span and runs deep into the cliff, horizontal cracks often develop in the roof, resulting in eventual collapse and the formation of an arch where the plane of collapse intersects the antechamber. Sometimes cave-ins in the antechambers of the lower caves directly affect the stability of the upper ones. Under these circumstances, stone slabs or reinforced concrete pillars have been used to provide support for suspended masses. In several stabilization projects, roof support measures were taken to pre-

vent further deterioration in the antechambers of Caves 351, 342, 334, 202–205, 218, 217, 61, 171, and 172, among others (Fig. 7).

Retaining walls

Retaining walls or buttress walls built with large stones or reinforced concrete have been constructed in front of the sloping faces of the grottoes to resist the lateral pressure of earthquakes and prevent bedrock from buckling outward along cracks parallel to the cliff. In the Mogao grotto stabilization projects, this retaining technique has been extensively

Figure 7
Section through a portion of a retaining wall.



employed and has been an important means of preventing bedrock from collapsing (Fig. 8). When a retaining wall is designed, architectural style must be determined while mechanical and structural requirements are simultaneously met. Practical installations, such as scaffolding with wooden walkways, were constructed to facilitate the work.

Reduction of overhangs

Unstable and dangerous external overhanging rock masses were reduced or rebated by chiseling. This was done not only to remove precarious rocks from the cliff edge but also to reduce the load on the bedrock (Fig. 5).

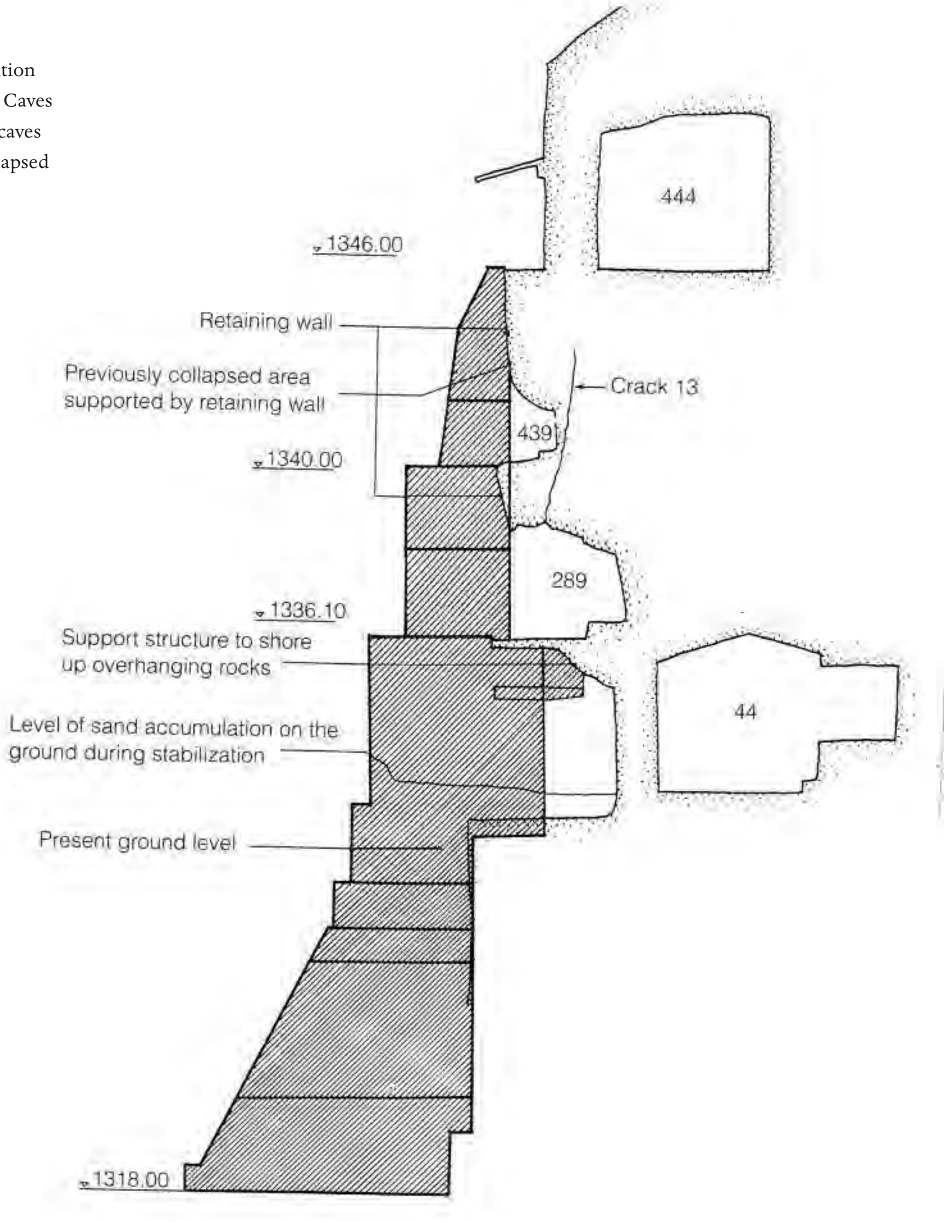


Figure 8
Section showing retaining-wall stabilization and support on the four levels between Caves 289 and 439. The front part of the five caves to the north and south of Cave 439 collapsed long ago.

Combined techniques

The following techniques were designed to combine roof-support and retaining-wall measures. Depending on the condition of the cliff face, support systems fall into three general categories: post-and-lintel, pillar, and retaining-wall structures. Post-and-lintel structures act only as apex supports. The base is built directly on the rock floor, and the lintel stone slabs are placed in close contact with the overhanging bedrock. When pillars are used, they are placed away from the antechamber walls to protect wall paintings. The retaining wall is used when stabilization of a fairly large area of the grotto cliff face is necessary. To satisfy various mechanical requirements, the retaining-wall structure should have sufficient mass and strength, and yet leave room for grotto entrances. It should be broader at the base and gradually decrease in cross-sectional area from base to top, forming what is essentially a pyramid-shaped stairway on which walkways can be built on different levels (Fig. 8).

Treatment of Foundations and Construction of Settlement Joints

In the process of stabilization, an effort was made to build all the supporting structures on bedrock. In some individual sections with overhanging rocks, however, the area requiring support was inevitably rather wide, and the support structure needed to be enlarged accordingly. If all such foundations had been built entirely on bedrock, it would have been necessary, in some cases, to construct foundations tens of meters thick. To solve this problem, an enlarged base area would be laid down first and observations made as to its degree of subsidence into the compressible, sandy soil below. Then the support structure would be constructed to a corresponding distance below the roof rock to be supported. After a period of gradual settling and establishment of relative stability, the space between support and roof would be filled. At that point, a tight support of the bedrock roof could be achieved. This mode of construction was used to support the roof of the antechamber of Cave 171.

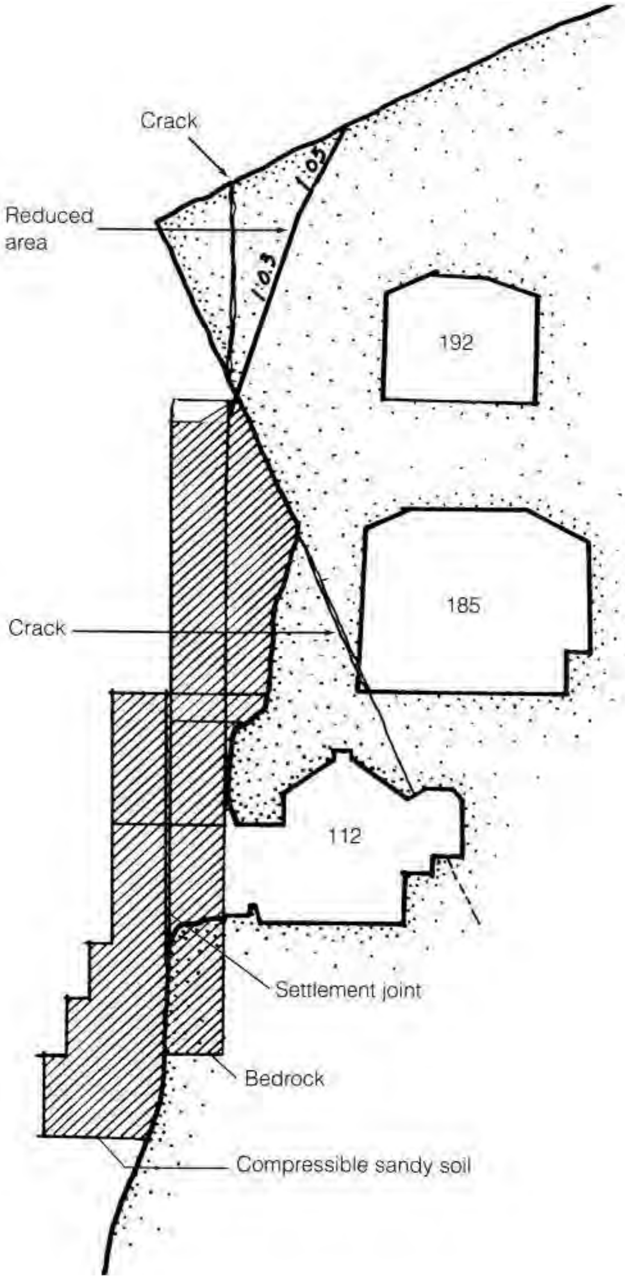
When a support structure needed to be wide enough for part of it to stand on bedrock and the other part on compressible soil, two separate foundations were constructed with settlement joints between them (Fig. 9). Since the outer parts of a structure may also settle to a certain extent, those areas of the foundation should be established on the same soil to maintain a uniform degree of subsidence for the entire structure. If a fairly large area and variable foundations were required, a horizontal deformation joint should be constructed every 20–30 m to serve as both the expansion and settlement joints.

Conclusion

In reference to the Mogao grotto stabilization project, the cultural relics administration stated:

> The principles of engineering design should give priority to ensuring the safety and stability of the grottoes and, at the same time, take into account

Figure 9
Section showing the foundation of a retaining or buttress wall. The foundation of the retaining wall outside the settlement joint is on compressible sandy soil. Reduction or rebating of the unstable, cracked section was carried out to remove dangerous rock and to reduce load.



the question of aesthetic style, so that major changes will not be made to the appearance of the Mogao grottoes. Therefore, it is essential to bring the structures of the stabilization project into line with the original style of the grottoes and make the utmost effort to preserve their original appearance.

On 9 August 1963, the late architect Liang Sicheng noted in his *Comments on the Dunhuang Conservation Project Program* (1963:239):

> Our main focus today is to build walls and basically preserve the appearance of the grottoes, which is the best we can do. Therefore, I endorse this general principle. . . . As far as I can see, everything of major value is housed inside the grottoes. . . . Our objective is to protect what is inside the grottoes by stabilizing them from the outside, and this objective of ours should be thoroughly understood.

After implementation of this project, which grew out of continuous investigation, a uniform style and local variations were achieved. The retaining walls follow the contour of the cliff face and rise and fall according to stabilization requirements and locations of the grottoes. The external wall paintings on the cliff face were preserved to the greatest extent possible, and all the exterior Tang and Song dynasty eaves were suitably protected. Railings, built with reinforced concrete, were installed on the walkways built outside the caves on all levels, presenting a visual contrast to the solid and often massive retaining walls. The concrete of retaining walls was given a sand-and-gravel-textured surface, in imitation of the conglomerate surface of the cliff itself, to provide a more natural appearance and avoid a monotonous texture for the exterior of the site.

Upon completion of the stabilization projects, access between caves was improved. Along with the structural changes, the walkways between the caves were built to take advantage of the engineering features. These included the various levels of step-shaped retaining walls with supporting cantilever beams protruding from them. Generally, the three stabilization projects implemented from 1963 to 1966 aimed at ensuring the safety of the grottoes. The rational approach not only solved the problem of access between caves but also gave rise to a solid, stable, simple, and graceful architectural style that did not overemphasize architectural form or decorative aspects and harmonized with the original appearance of the grottoes.

Between 1984 and 1985, these principles were again followed in reinforcing the twenty-six caves in a 172 m section to the south of Cave 130. The conservation of this area—the most desolate and dilapidated of the Mogao grottoes—marked the initial completion of the stabilization projects and the macroconservation stage of the site. This created favorable conditions for overall scientific research on further aspects of protection of the Mogao grottoes, as well as for the conservation of Chinese cultural heritage.

Notes

1 From 1 November to 31 December 1962, the Dunhuang group of the second survey team under the First Design Institute of the Ministry of Railways carried out on-site engineering, hydrological investigations, and grotto surveys at the Mogao grottoes.

2 The Bridge and Tunnel Division of the First Design Institute carried out the design according to the directions of the Ministry of Railways and the Ministry of Culture. The construction team was organized by the First Construction Division of the Urumchi Railway Bureau, under the Ministry of Railways.

3 Two obvious cracks were measured in Caves 438 and 445. They widened from 0.5 mm in 1959 to 1.0 mm in 1962.

4 Recorded in the *Tablet of Zhang Huaishen* of the late Tang dynasty, kept in Cave 17 of the Mogao grottoes.

Reference

Liang Sicheng

1963 *Comments on the Dunhuang Conservation Project Program.* Vol. 4 of his collected works. n.p.

Stabilization and Consolidation of the Kizil Grottoes

Jiang Huaying and Huang Kezhong

The Kizil grottoes, located 50 km east of Baicheng county, Xinjiang Uygur Autonomous Region, were excavated during the third to the ninth century C.E. and are considered a jewel of the ancient Silk Road. The murals, sculptures, and architecture of the grottoes illustrate how Chinese Buddhist art was adapted from foreign grotto art. The scope of this site is second only to that of the Mogao grottoes at Dunhuang. The Kizil grottoes provide important data for the study of art history and the history of cultural exchange between China and foreign countries and are of great significance among the grotto sites of China.

This artistic treasure has been subjected to more than a thousand years of damage caused by natural weathering, looting, and ravages that occurred during foreign invasions and religious wars. Wall paintings and clay sculpture in the caves have been destroyed by weathering, damaged by knife and ax blows, blackened by smoke, and burned by fire; only a few wall paintings in the caves remain relatively intact.

After the founding of the People's Republic of China, the Kizil grottoes became a matter of great governmental concern. Because the caves were excavated in a loosely cemented rock formation, the strata tend to collapse when affected by water. In addition, prolonged erosion by natural forces has resulted in the development of ravines above the grottoes and cracks inside the caves. Rainwater seeping into the caves has caused extensive salt efflorescence, flaking, and separation of the wall paintings from their support. Roof collapse and rockfalls are common. In a preliminary survey of the caves, most of the front chambers were found to have collapsed, and the temporary suspended walkways were very shaky.

In 1986, a conservation team was invited to undertake the task of planning the restoration and reinforcement of the Kizil grottoes (Kizil Design Group 1987). Work was formally begun in 1988, after two years of surveying damage, conducting on-site experiments, and evaluating plans. In 1989, the work of reinforcing Caves 2–30 and 31–48 (the first and second repair and stabilization phases, respectively) was completed. After an initial inspection, the reinforcement was found to be effective and the quality of the construction complied with design requirements. Following is a summary of the principal working methods used.

Geology

The Kizil grottoes are located in the contact zone between the Kuche Baicheng depression and the Qiulitake uplift of the east-west Tianshan complex tectonic zone on the north side of the Weigan River. Two active faults are located at the south bank of the river but are not considered significant, as the tectonic stresses at the grotto site itself are relatively stable.

On the basis of records published in 1985 on seismic activity in Xinjiang, an earthquake greater than magnitude 6 on the Richter scale has not occurred over the past 270 years in this region. Because of the frequent low-magnitude earthquakes in the Baicheng and Hojing seismic zones, it is considered unlikely that an earthquake of magnitude 7 or greater will occur in this area over the next 100 years. The danger of an earthquake with a magnitude around 6 does exist, however; and the area is currently designated as a magnitude 8 earthquake zone.

The strata of the grottoes are Pliocene epoch (N_2^4), grayish brown and grayish yellow sandstone interbedded with mudstone and occasionally with conglomerate showing significant variation in the lateral facies. The strata consist of 70% sandstone and 30% mudstone. Sandstone contains approximately 36.5% calcium carbonate along with soluble salts, such as calcium bicarbonate, $Ca(HCO_3)_2$; magnesium chloride; sodium chloride; and gypsum. The rock is weak, with a poor degree of cementation by calcareous materials; it crumbles into sand when wet. The mudstone is mostly silty with a relatively low degree of cementation. The cement is carbonate (26.41%) and organic materials. X-ray diffraction analysis of the clay suggests that it consists mainly of calcium and magnesium montmorillonite (5.72%), illite, and trace amounts of kaolinite. This argillaceous rock expands on contact with water and weathers easily.

The mechanical strength of all the rock is extremely low. Point-load tests show that the tensile strength of the weathered sandstone is 0.66 kg cm^{-2} and the compressive strength is 13.93 kg cm^{-2}. The tensile strength of the semiweathered sandstone is 0.86 kg cm^{-2}, and its compressive strength is 18.23 kg cm^{-2}. The tensile strength of the semiweathered mudstone is 23.58 kg cm^{-2} and its compressive strength is 497.8 kg cm^{-2}. The large area of collapse at the Kizil grottoes was caused by weathering of the poor rock quality.

State of Deterioration

The Kizil grottoes consist of 236 caves distributed over a distance of 2 km. Muquan canyon divides the site into four natural areas: west, east, the interior, and the area to the rear of the mountains. The caves have suffered severe deterioration and damage. About 60% of the caves have exposed main chambers caused by the collapse of the front chambers. Even some of the relatively intact caves are in danger of collapse. Preliminary assessment showed that only ninety-two caves with murals and statues, four with inscriptions, and forty-five relatively complete monks' chambers remain intact. Many types of damage are apparent around the grottoes, the primary causes of deterioration being crisscross cracks in the rock and water erosion.

The Kizil grottoes were cut into a steep cliff face. The weight of the rock itself, its geological structure, and the force of the lithification process have produced natural stresses inside the rock; in other words, irrespective of the caves, the rock is constantly being subjected to natural stresses, and the state of these stresses changes over time. If there are no large-scale disturbances, these stresses will gradually stabilize throughout the rock. The introduction of the caves disturbed the stress field of the rock body, redistributed the stresses, and introduced new avenues of energy release that formed many sets of cracks.

In the grotto area, there are two sets of cracks. One set of cracks, caused by tectonic movement, consists primarily of shear fractures with a northwest strike of 330–340°. The other set consists of tensile cracks, generated after excavation of the grottoes, parallel to the cliff face to the west and east of the canyon, with a northwest strike of 290–330°. These two sets of cracks crisscross each other and cut the cliff rock into many fragments of different sizes. Inspection of the main 111 caves revealed that 59 caves have cracks, and some have three or more. Many caves are cut all the way through by cracks. The action of external forces and weathering on the fragmented caves have caused many of them to collapse progressively from the outside walls toward the inside. Precarious overhanging rocks can be found almost everywhere within the grotto area. In the area west of the canyon, there were eleven locations with unstable overhanging rocks of about 314 m^3 in total volume.

Water erosion has damaged the caves in two ways. First, heavy rain and floodwaters created numerous gullies on top of the grottoes and in the cliff rock. The preliminary assessment revealed about seventeen large gullies and thirty-two small ones within an area of 1 km^2. These gullies cut into the cliff rock, making collapse inevitable. Some of the gullies penetrate the roofs of caves and allow water infiltration that erodes the surface of the rock and causes spalling of the wall paintings.

A horizontal hole was drilled in a weathered zone in the western region of the Kizil valley, and a weathering depth of about 2 m was found. During heavy rain, the rainwater—combined with large amounts of mud—flows straight downward, and sand carried by the water produces scratches, grooves, and mud stains on the murals. Analysis of the archaeological data showed that about 2–6 m of the cliff face had already collapsed. A large quantity of collapsed rock—along with the mud and sand that had washed off the top of the grottoes—buried many caves and blocked entrances, posing problems for protecting the grottoes, as well as severely limiting access for visitation.

Reinforcement

Reinforcing the Kizil grottoes was a large-scale repair project. The geological and geographic environment of the grottoes is complicated, and the project was difficult and dangerous. The design and implementation of the entire project were based on the results of rigorous scientific experiments. Detailed surveys of the grottoes, repeated tests, and consultation with

experts were used to develop a comprehensive plan that involved a combination of roof support, anchoring, and chemical consolidation.

Anchoring of unstable rocks

Anchoring involved the insertion of metal bolts of different lengths into the rock body. These bolts penetrate cracks to anchor precarious rocks against firm bedrock. In the course of repairing and reinforcing the caves, the degree of stability of the caves was found to be related to that of the mountain as a whole. The caves are surrounded by mountain, and it was necessary to stabilize the mountain to ensure the safety of the grottoes. The anchoring method must make full utilization of the strength of the rock strata, release stress concentrations, and inhibit further development of tensile cracks. To ascertain whether the anchor bolts could provide sufficient anchoring force, and whether the depth of the anchoring was suitable in the particular rock of the Kizil grottoes, the Gansu Construction Research Institute and the Gansu Fifth Construction Engineering Company were asked to perform extraction tests of the anchor bolts. The tests were carried out on sandstone in the vicinity of Cave 30 and on mudstone in the vicinity of Cave 80, west of Muquan canyon. Sixteen-gauge, cold-drawn, manganese spiral-steel rods with a design strength of 4,500 kg cm^{-2} were used. Bolt no. 257 was anchored in sandstone and bolt no. 156 was anchored in mudstone. The results of the extraction tests are shown in Table 1.

When the anchor depth in the sandstone reached 50–60 cm, the extraction-resistance force was about 14 t, demonstrating a sufficient anchorage strength. In mudstone, however, the design-required anchorage strength could not be obtained until the depth was 110–160 cm. During the experiments, it was found that bolts could be easily inserted into 100–200 cm deep drill holes, which were filled with ordinary concrete and compression grouting. However, it was difficult to insert the bolts by hand into holes 300–400 cm deep because of the strong water-absorbing capacity of the Kizil sandstone; the concrete grout lost water quickly to the surrounding rock, causing the concrete to become less fluid. The problem was resolved by either wetting the holes before grouting or using another type of water-retaining concrete. Results demonstrated that reinforcing dangerous loose rock with bolts is effective and feasible.

Protection by consolidation

The collapse of some of the Kizil caves is directly related to the physical and chemical properties of the rock itself and to the erosive action of natural weather stresses of the external environment on rock. To slow deterioration, the rock surface was treated with a protective chemical consolidant to inhibit weathering and to increase its strength and water resistance.

Three types of materials—organic (methyltrimethoxy silane), inorganic (potassium silicate), and a mixed organic-inorganic (of the first two)—prepared in fifteen formulations were tested on the basis of the

Table 1 Test results on rock bolts grouted with standard concrete

	Rock bolt				Pull out test					
Sample No.	Diameter (cm)	Yield strength R_g (kg cm^{-2})	Anchoring depth (cm)	Hole diameter (cm)	Pulling force P (kg)	Stress on bolt σ_a (kg cm^{-2})	Cohesion between bolt and grout	Cohesion between hole and grout	σ_a/R_g	Bolt-yielding characteristics
A-1[a]					15000	5893	49.18	16.37	1.29	Bolt yielded
A-2	1.8	4565	54	5.4	15000	5893	49.18	16.37	1.29	and pulled out
A-12					1400	5500	45.90	15.28	1.20	of grout.
A-3					13600	5343	44.59	14.86	1.17	Bolt broke
A-4	1.8	4565	54	5.4	14000	5500	45.90	15.28	1.20	and pulled
A-5					14000	5500	45.90	15.28	1.20	out of grout.
B-1[b]					6000	2357	19.67	7.86	0.51	Bolt and grout
B-2	1.8	4565	54	4.5	7000	2750	22.95	9.17	0.60	were pulled
B-3					6000	2357	19.67	7.86	0.51	out together.
B-7					13500	5304	22.13	8.84	1.16	Bolt and grout
B-8	1.8	4565	108	4.5	13000	5108	21.31	8.52	1.12	were pulled
B-9					12000	4715	19.67	7.86	0.03	out together.
B-13					>14000	>5510	15.30	6.11	>1.2	Bolt yielded
B-14	1.8	4565	162	4.5	>14000	>5510	15.30	6.11	>1.2	but was not
B-15					>14000	>5510	15.30	6.11	>1.2	pulled out.

[a] A series = bolts anchored in sandstone.

[b] B series = bolts anchored in mudstone.

principal lithological characteristics and climate of the Xinjiang area. Four of these preparations were selected for field tests. Field studies were also conducted of spray application techniques and the composite organic-inorganic material was finally selected. Clear improvement of the properties of the rocks was obtained after they had been treated with this material.

Test results

The compressive strength and tensile strength obtained using a point-load test machine were 47.51 kg cm^{-2} and 2.26 kg cm^{-2}, respectively. These values were 3.4 times higher than those of the weathered rock and 2.6 times higher than those of the semiweathered rock.

The porosity of the rock as determined after treatment was 0.016647 cm^3 g^{-1}, which is about 85% lower than the original porosity of 0.11267 cm^3 g^{-1}.

The original sandstone disintegrated, and the sand was dispersed after ten minutes of soaking in water. The treated rock remained intact even after one year of soaking.

The untreated sandstone had a capillary rise of 5 cm in ten minutes, whereas the treated stone had a capillary rise of 2 cm in two hours (Table 1).

The penetration depth of this chemical material in the rock was 5 cm in the laboratory and 4–5 cm on-site.

Freeze-and-thaw, stability, and aging tests were also performed. All of the data demonstrated that this consolidant was clearly effective in decreasing further weathering of the rock. This finding was further corroborated by the experts at the Kizil survey and design approval meeting.

Tests of walkway cantilever beams

The walkway of the Kizil grottoes was designed on the basis of tests on cantilever beams conducted by the Gansu Fifth Construction Engineering Company and the Gansu Construction Research Institute. The test data are shown in Table 2.

Load tests were carried out by adding loads to the end of the cantilever beams. The beams, of reinforced concrete, were anchored at a depth of 4 m into the sandstone and mudstone. The moment of fracture resistance in sandstone was 2.88, which was 1.61 times the designed value. The moment of fracture resistance in mudstone was 2.26, which was 1.60 times the designed value. On-site experiments showed that when the load on the outer edge of the beam in mudstone reached 3.5 t, one visible crack formed, with complete extraction of the beam occurring at 6 t of load. The test data indicated that these cantilever beams, like ordinary cantilever beams, could satisfy the design requirements in both sandstone and mudstone. Only when the load was too high did the bending angle at the root of the beam exceed the required limit. This is because the Kizil rock is weak. When the steel bolts were stressed and pulled outward, the base of the beam was extruded and the rock was fractured. The method for solving this problem was to install a 200 × 600 mm reinforced-concrete foundation at the base of the walkway beam to increase the area bearing pressure, disperse pressure at the base, and eliminate the destructive effect caused by the bending angle.

Table 2 Designed and tested values for beams

	Anti-bending moment T–M			Deflection under standard load				Breakage strength		
Beam number	M_T (calculated)	M_T' (measured)	M_T'/M_T	f_T' (mm)	f_R' (mm)	f_T'/L_0	f_R'/L_0	M_p/T–M	K_p	Note
No. 215 (sandstone)	1.747	2.88	1.61	1.495	1.07	1/735	1/1028	6.78	4.43	Rebar yielded first, then bent and broke.
No. 150 (mudstone)	1.41	2.26	1.60	8.98	6.38	1/122	1/172	5.65	3.69	Base of the beam was 350 mm high. Beam yielded and broke at the base.

M_T' values taken at the first appearance of a visible crack in the beam.
f_T' is the measured bending.
f_R' is the bending resulting from rotational displacement of the beam.
Designed bending moment is 1.53 $^{T–M}$.

Major Measures for Stabilizing and Reinforcing the Kizil Grottoes

The caves of the Kizil grottoes are crowded together and extend continuously over a distance of several kilometers. They show different types of damage and different levels of deterioration. For this reason, it was necessary to repair the most valuable caves and to address the overall effect in regions that are clustered with caves. After an overall survey was conducted, the western part of the valley was divided into four working sections: Caves 2–30 composed section 1, Caves 31–48 made up section 2, Caves 57–70 composed section 3, and Caves 76–82 were designated as section 4. Work on these four sections were to be completed in two stages. At present, the first and second sections have been completed.

Emergency reinforcement of the cliff rock and caves

The major reinforcement work in the first and second sections involved implementing retaining walls and roof supports and anchoring large areas. The cliff is discontinuous with many structural entities. The interior has undergone weathering, fracture, cracking, and cutting, with independent and partially independent blocks being formed. However, these blocks have their own self-supporting force and this needs to be taken into consideration in the reinforcement.

In reinforcing the cliff rock in the first and second sections, different techniques were applied in accordance with the different conditions of each cave. Three levels of caves in the vertical direction were grouped in the first working section. The front chambers of these caves had collapsed, and some had very thin roof rock. Stress-relief cracks had occurred inside many of the caves, making it unsuitable to insert bolts into the rock. Retaining walls were the principal means of reinforcement used, supplemented with bolts. Archaeological data were used as references to restore parts of the front chambers to their original shapes. Concrete mortar was poured on-site for use in the restoration of the entrances and walls of the caves. For example, portions of the front walls of Caves 2–6 were anchored to the wall of the cave entrance and to the cliff rock in a single entity by bolts, thereby combining partial restoration and reinforcement.

The caves in section 2 are scattered. The front chambers of these caves had collapsed, whereas the rear chambers remained intact. Most of these caves are located at the base of the cliff. For this reason, the anchoring technique used for large areas was principally applied in this section. Bolts 16 mm in diameter were spaced 1.5–2 m apart and arranged in a plum-blossom shape with an anchor depth of 2–4 m. Where cracks were present, the anchor depth was about 0.5–1 m beyond the location of the last crack.

One case that deserves particular comment involved a large, precarious rock about 10 m high, 3 m wide, and 2 m thick that constituted the wall between Caves 33 and 34. A crack about 10–20 cm wide ran through the rock from top to bottom. In front of the rock were some remains from the front chamber that were used as an archaeological reference point. There was no alternative but to preserve this rock, as it could not be ignored for structural reasons. In the course of the work, two waist frames

were installed in the middle of the rock to attach it tightly to the cliff in back and prevent it from collapsing during drilling. Bolts were installed in a plum-blossom pattern. To prevent further erosion by rainwater, the crack in the rock was filled with concrete mortar and the surface sealed with cement. This not only eliminated the dangerous condition, but it also preserved the historical evidence of the original shape of the grotto.

Water control

Water damage to the Kizil grottoes is primarily manifested in erosion by rainwater and surface runoff from the rock. The climate of the Xinjiang area is characterized as arid with low precipitation. The annual precipitation of the Heizi area is only 94.9 mm, and most of the rainfall occurs in June, July, and August. Because there is no soil, surface runoff occurs immediately during heavy rainfall. This water exerts a strong eroding force on the cliff rock, with numerous gullies of different sizes forming rapidly, some reaching several tens of meters in depth. These gullies create the greatest danger of collapse to the grottoes.

From the top of the grottoes, the gullies present a crisscross pattern. In the western region of the valley alone there are nineteen gullies of different sizes, five of which were directly endangering the caves, either undermining the bases or eroding the tops of the cliffs. Moreover, new gullies are developing constantly.

Under present conditions, it is difficult to eliminate the danger of erosion completely. The current policy is to treat gullies that are directly threatening or directly eroding the caves. In the course of conducting a comprehensive survey of the gullies, a portion of an ancient sandstone brick wall was discovered in the fore portion of the top of the cliff in the western region of the valley. The direction of the wall was essentially parallel to the cliff face. It was presumed by the Guizi Grotto Research Institute that this wall may have been built in ancient times to divert sand and floodwaters. If a new water-diversion wall were to be constructed at the top of the cliff in imitation of this ancient method, its position would have to be moved to the rear. However, this still would not solve the drainage problem on the front slope. Therefore, interception, diversion, and conveyance of the surface runoff away from the caves in accordance with the different specific conditions of each situation were adopted insofar as possible to eliminate severe erosion caused by runoff.

In section 1, the caves are very close together. Several key caves on the upper level are subjected to continuous erosion by runoff. The tops of Caves 14–17 were already very thin. Because rainwater often seeps into these caves, it was important to have a good drainage system. The principal method taken here was to dig a drainage ditch running east-west about 7–8 m from the top of Cave 9. The western end ran through the large gully in the eastern side of Caves 2–7 and the eastern end reached the large gully on the eastern side of Cave 17. The southern wall of the drainage ditch was high, and its other wall was low. In this way, it has intercepted the flow from the roof of the cliff in the north and diverted the

flow into the gullies in the east and west. More than a year of study has shown that the results have been very good and that the drainage ditch successfully intercepted and diverted the flow.

It was difficult to build a retaining wall and drainage ditch on the front slope of the cliff top of section 2 caves. Instead, a reinforced concrete awning was built at a fixed height at the fore wall of the cliff. This served to prevent water from directly eroding the caves.

External awnings or shelter structures have been considered. The design should be simple and practical. Anchor bolts used to reinforce the cliff face could support the awning. However, aesthetically it would be best to integrate the awning style with the appearance of the caves and add arched or trapezoid-shaped figures.

Restoration of entrance walls and single-chambered caves

Almost all the Kizil caves are either rectangular or square in plan and have front and back chambers. The front chamber usually has a niche on the cliff side and a statue inside the niche. The inner chamber has a passageway to the side, and to the rear of the passage way is either an arched or a squared ceiling. Some of the rectangular caves have central pillars and arched ceilings. Most of the front chambers of the caves are collapsed, and only their inner chambers remain intact. Reconstruction of an entrance wall often involves either the front or the back wall of the front chamber. Accurate reconstruction of these areas is advantageous for the long-term protection of the caves, and also for future research on them. The stability and safety of the cave interiors also obviously depend on proper restoration of these areas.

The Kizil work section 1 divides naturally into three major groups: Caves 2–6, 7–17, and 27–29. Different techniques were used to repair the entrance walls in these three groups. Caves 2–6, which served as the monks' living chambers, had very thin roof strata. Most of the entrance walls had been temporarily restored using mud bricks that did not have any reinforcing effect and resulted in changes of configuration.

The front chambers and parts of the inner chambers of some caves no longer exist. For example, the inner chamber of Cave 3 was half collapsed and its entrance wall had been restored. In the course of the current reinforcement, the entrance wall was removed and cleaned, exposing the base of the walls in the inner chamber. The cave was then restored with reinforced concrete mortar to its original shape and style. A small area of original gypsum floor remaining in the front chamber was used as a basis for the restoration of the front chamber. However, there was no information about the depth of this chamber or the shape of the roof. For this reason, a structure was built outside the entrance wall to indicate that there had originally been an outer chamber. Other caves were restored in the same manner. To avoid a rigid and dull appearance, the inside of the entrance wall was made smooth and perpendicular to the ground surface,

and the outside surface of the entrance wall was made to resemble the natural cliff.

Caves 7–17 are, for the most part, decorated with exquisite murals and have arched ceilings and central supports. All the front chambers of this group had collapsed. However, the inner chambers are well preserved. The cave entrance walls support the roof and have an external frame structure that indicates the previous existence of a front chamber.

Caves 10–17 are distributed vertically in two levels. When the upper-level caves were reinforced, the entrance walls had to be supported on bedrock, and it was thus necessary for the walls to penetrate through the caves at the lower level. In the reconstruction, a reinforced concrete pillar-beam was used. The intermediate walls of the upper caves were built using hidden pillars, either seated on the bedrock at the lower level or directly positioned on the horizontal beams at the tops of the entrance walls of the lower-level caves. A walkway between the levels has preserved the layered pattern. Cave 7 is on the westernmost end of this group and is very close to the area threatened by the gullies. Its front chamber had collapsed in the past, and the extant eastern half of the inner chamber was on the verge of collapse due to a gully on its western side. In the process of repairing this cave, loose dirt was first removed and a hole was dug into the bedrock. The floor was then restored with reinforced concrete mortar to its original level. The style and the size of the cave were reconstructed based on estimates made from the remains of the cave. After this work, the inner chamber of Cave 7 was completely protected.

The wooden walkway

The Kizil grottoes were excavated on a high, steep cliff face. Some caves were made more than 50 m above the ground. Most of the original walkways or stairs built along the cliff face had deteriorated, and some of the recently built simple, crude ladders were also on the verge of collapse. Sand that had accumulated in front of the caves buried many caves and blocked the walkways, making many caves inaccessible. In response to the development of tourism, the major objectives of this project were the construction of a new walkway, the removal of accumulated sand, the filling of cracks, and the paving of new roads. The walkway was designed to connect the scattered caves, thus facilitating visitation, while also harmonizing with the natural environment. Therefore, the floor of the walkway was left unpainted, with the original color of the concrete being maintained, and the railings were painted yellow to match the yellow-sandstone color of the grottoes.

Archaeological survey work

Many caves of the Kizil grottoes are buried beneath rock debris from the collapse of other caves. Cave 1 is a relatively intact cave that was discovered in 1973. Before conducting repair and reinforcement, exploratory work was needed to locate any caves or relics that may have been buried

beneath it. The intent was to avoid affecting future archaeological excavations by installing permanent structures on top of buried caves.

The authors asked the Railway Building Institute to conduct a geophysical exploration using C-1 microdepth measuring equipment (Zhong 1983). The principal survey sites were the front slopes of the sections between Caves 6 and 27, 52 and 70, and 110 and 120. An overall area survey was performed first by the intermediate gradient method. In regions showing anomalies, three-electrode electrical depth measurements were conducted. Final confirmation was carried out by the five-electrode vertical depth-measurement method. Results indicated that there were caves buried beneath both the first and the second work sections. Excavation was carried out by the Xinjiang Archaeology Research Institute.

After Cave 1 was excavated, the relics beneath it were found to be damaged because protection work had not kept pace with the excavation. In light of this finding, the principles adopted for future excavation were (a) that sections and caves that do not have an effect on the course of the project will not be excavated; and (b) that systematic excavation of the caves that must be excavated will be conducted by specialized archaeologists who will prepare the excavation reports and do preparatory work for the scientific conservation of the relics found.

Conclusions

All the reinforcement and repair projects in the first and second sections of the Kizil grottoes and all other work have essentially been completed except for chemical consolidation, which was limited by engineering considerations. The extent of the work completed to date accounts for only a small portion of the tasks of repair and conservation of the Kizil grottoes. There is certainly much to be learned, and it is the authors' sincere hope that their colleagues in the field of grotto stabilization and consolidation will provide valuable suggestions to ensure the successful completion of the repair and reinforcement of the Kizil grottoes.

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Application of Cartridge-Type Grouting in Grotto Conservation

Zhong Shihang

In the field of grotto conservation, it is common practice to use concrete-mortar grouting and steel bolts for the reinforcement of rock and slopes and in the construction of new walkways. Comparatively speaking, concrete grouting bolts are inexpensive, resistant to aging, and do not pollute the environment.

The general procedure is to begin by pumping the concrete mortar into the grout hole and then to insert the steel bolt. Pumping the concrete is a troublesome procedure. A pump is required, and sometimes a compressor, as well; and if the grout hole is inclined upward, complete filling of the grout hole with mortar cannot be guaranteed. However, the technique of applying a cartridge-type grouting is simple and makes it easier to fill a grout hole with mortar. The author frequently uses a fast-cure thioaluminate cement developed by the Chinese Academy of Railway Sciences (Table 1). This cement is noncorrosive and undergoes only very slight expansion. The cartridge-type grout made with this cement has been used extensively in railway tunnels, water tunnels, grotto consolidation projects (e.g., Longmen grottoes), and the construction of walkways on cliff faces, all with excellent results.

This grouting technique is simple to perform and ensures that the holes will be filled with mortar. The thioaluminate cement is mixed with sand at various compounding ratios. A TS-type additive[1] is added, and the mixture is then poured into a specially designed paper cartridge. The diameter of this cartridge, which is 20–25 cm in length, can be designed to fit the size of the grout hole. The cartridge paper is tough when dry and

Table 1 Physical properties of cartridge-type, fast-cure concrete mortar

Cement type	Compressive strength (MPa) Curing time		
	4 hours	3 days	Anti-freeze
Fast cure	>10	>25	D 200
High strength	>15	>40	D 200

Figure 1
Soaking cartridges in water.

has an extremely high water-absorption capacity. The cartridge is soaked in water immediately before it is inserted into the bolt hole (Fig. 1); after it has been soaked in water, the paper can easily be torn. The water rapidly permeates the bag to form a concrete mortar with a water:solid ratio of 0.4:0.5 within one to three minutes. At this point, the cartridge is rigid and can be inserted easily into the bolt hole. A steel bolt can be placed into the bolt hole after it has been calculated that a sufficient number of cartridges are in place. At this time, the paper cartridges will break and release the mortar into the hole, with the mortar completely filling the hole and enclosing the bolt. Better results are achieved if the steel bolt is pushed in using a rotational motion. Setting of the mortar begins in less than eight minutes; complete setting can be adjusted by the user to between ten and forty minutes by varying the quantity of additive. Within two to four hours after the bolts have been inserted, resistance to extraction can reach 20–40 kN at room temperature and can increase to more than 80 kN after ten hours.

Extraction-resistance tests

The author tested the resistance to extraction of this grout at the Longmen grottoes (Table 2). Ten steel rods of 20 mm in diameter and 2.5 m in length were inserted into holes with diameters of 40–50 mm. Fast-cure cement was used, and resistance to extraction after twenty-eight days exceeded 140 kN.

Cantilever beam tests

The author further tested this grouting technique in the construction of cantilever beams at the Longmen grottoes. Two rows of grouted bolts were anchored 2 m into a rock body in a vertical arrangement with 1.5 m of the bolts exposed. The free ends served as the main reinforcing bars, and concrete slabs were formed between the two beams at a distance of 2 m. Loads of up to 20 kN were applied to the outer edges of the concrete slabs, with the bending of the beams remaining within the design limit.

Table 2 Extraction-resistance tests

Bolt no.	Resistance to extraction (kN)		
	Time		
	4 hours	6 hours	8 hours
2		47	56
3	27		>100
4	27	>100	
5	17	>100	
6		61	

Fast-cure concrete mortar. Hole diameter, 45 mm; rock bolts 2.5 m long and 20 mm in diameter.

There was no residual deformation after loading. The beams' rupture load reached 50 kN, which is far beyond design requirements.

Grout Filling Test

Complete filling of the bore holes with mortar and bolting to the full anchoring depth of the bolts are the essential criteria for the long-term durability of any anchoring project. Statistically, the percentage of anchorings failing to meet quality standards because of incomplete filling with mortar reaches 20–30%. For many years, a good test of the adequacy of mortar filling was not available.

At present, tests of resistance to extraction are used to evaluate the quality of concrete grout. However, despite the poor quality of the grout filling, many rock bolts exhibited very high resistance to extraction. Theoretically speaking, as long as the length of a filling is greater than forty times the diameter of the steel bolt, the bolt will not lose anchorage until it is pulled to the point that the neck of the reinforcing bar contracts. Therefore, equipment and methods have been sought for measuring the completeness of mortar filling directly. Thurner (1983) proposed the principle of using an ultrasonic method to determine the quality of fillings. Over a ten-year period, several instruments were developed based on this principle. However, these instruments were only capable of determining smaller gradations in relation to the bolt-extraction force and did not directly reflect the degree of mortar filling.

On the basis of Thurner's principle, the author quantitatively investigated the relationship between the amplitude of the reflected wave and the completeness of mortar filling, and also examined different measuring methods and instruments. Thus, it became possible to use the percentage of mortar filling to evaluate the quality of the grouting. Accuracy by this method can reach 10%.

Principles

The basic principle of the method is as follows: When a pulse is generated on the outer end of the bolt, the ultrasonic waves propagate along the bolt and are reflected back when they reach the inside end of the bolt. The reflected wave is detected on the outside end of the bolt. If the reinforcing bar is completely enclosed by the concrete mortar and the mortar is adhered to the surrounding rock, the ultrasonic wave will, during the course of propagation, be continuously transmitted from the reinforcing bar through the concrete mortar into the rock. Consequently, there will be great energy loss, and the reflected wave as measured at the outside end of the shaft will be of low amplitude and may not even be determinable. If there is no filling with mortar grout, then there is merely an empty shaft in which the ultrasonic wave will be propagated in the reinforcing bar with little energy loss, and the amplitude of the reflected wave received will be greater. If there is incomplete filling with mortar grout, there will be an intermediate state, and the intensity of the reflected signal will be intermediate between those previously mentioned. Therefore, the degree of

mortar filling can be determined (Bergman et al. 1983). Low-frequency waves, such as 10-kHz sonic waves, have proved sufficient for this testing.

Equipment

The equipment required for this testing includes

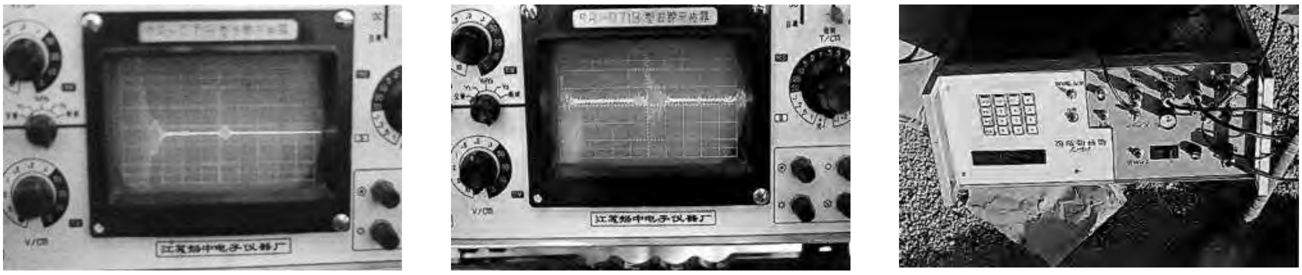
- a pulse generator, installed on the exposed portion of the bolt, that can generate sonic waves of 10-kHz frequency;
- a coupling device, installed at the outside end of the shaft, with water between the inside wall and the shaft body as the coupling agent; and
- a recorder that receives the signal propagated from the head and displays the length of the bolt and the degree of mortar filling (Fig. 2a–c).

Method of measurement

Three to four groups of standard grouted bolts were installed in different types of rock on the basis of the design parameters, with one or two grouted bolts in each group. Three groups of grouted bolts with 70%, 80%, and 90% mortar filling were tested. The degrees of filling were set as grade A for over 90% filling, grade B for 80–90% filling, grade C for 70–80% filling, and grade D for less than 70% filling. Grades can be set as desired on the basis of the design, with four as the maximum number of grades that can be set for this instrument.

The amplitude of the reflected wave is then determined on these standard grouted bolts, an average value being taken when there is more than one grouted bolt in a group (Fig. 3). These values serve as calibration standards for other grouted bolts. The calibration values are input into the instrument before performing determinations on other grouted bolts. When other determinations are made, the lengths of the grouted bolts and the degree of mortar filling can be displayed automatically by the measuring instrument.

When determinations are to be made on individual grouted bolts, the outside ends of the grouted bolts should first be smoothed (they may be sawed flat) and the pulse generator attached. Then the receiving head of the coupling device is affixed to the outside end of the shaft body.



a b c

Figure 2a–c
Tests for completeness of filling: (a) drill hole is partially filled with grouting material; rock bolt is 2 m in length and 16 mm in diameter; (b) drill hole contains no grouting material; rock bolt is 2 m in length and 16 mm in diameter; and (c) readout equipment for determining completeness of grout filling.

Figure 3
In situ test of the degree of mortar filling.

Water is then poured to fill the inside wall of the coupling apparatus as well as any voids that may exist on the surface of the outside end of the grouting bolt.

The instrument monitors the reflected signal in wave form by means of an oscilloscope. When the operator has manually adjusted the instrument until reflected signals appear, the instrument automatically displays the length of the grouted bolt, the amplitude of the reflected wave, and the degree of mortar filling.

Results of determinations

Accuracy of measurement is a point of interest during testing procedures. The first criterion of accuracy is whether values obtained by repeated determinations of parameters for the same grouted bolt and for bolts with the same or different degrees of filling are consistent. The second criterion is whether the results determined for different grouted bolts conform to the actual circumstances of those grouted bolts.

For this purpose, the author tested large numbers of anchored bolts with known degrees of mortar filling and has also requested other researchers to prepare grouted bolts of known characteristics and to test the methods and instruments. Table 3 lists the data obtained in a tunnel project. Two bolts were inserted for each degree of filling. By referring to this table, the accuracy of the measurements for grouted bolts under the same conditions can be checked and different degrees of mortar filling can be differentiated. It can be seen that variation between the two measurements obtained from the two bolts situated in the same grout was considerably less than 10%.

Table 3 Filling tests

Bolt no.	1 & 2	22 & 25	8	10	11	18
Anchoring depth (m)	2.0	3.8	3.8	2.0	3.8	2.0
Filling (%)	100	70	100	70	65	0
Amplitude	129/132	66/163	115/118	171/175	168/171	151/154
Difference	3	3	3	4	3	3

Table 4 In situ tests at Chen village tunnel (partial results)

	Control bolts			Test bolts			
Bolt no.	9	24	25	8	11	16	22
Anchor depth (m)	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Filling (%)	90	80	70	100	85	50	70
Classification	A	B	C	A	B	D	C
Depth (m)				3.6	3.7	3.7	3.6
Amplitude	125	145	160	114	168	over	156

Data shown are for bolts 22 mm in diameter.

Table 5 In situ tests at Chen village tunnel (partial results)

	Control bolts			Test bolts		
Bolt no.	3	4	6	12	18	15
Anchor depth (m)	2.0	2.0	2.0	2.0	2.0	2.0
Filling (%)	100	90	80	90–100	90	50
Classification	A	B	C	A	B	D
Depth (m)				1.7	1.9	1.7
Amplitude	138	154	168	144	151	206

Data shown are for bolts 18 mm in diameter.

Tables 4 and 5 show the correlation between the results of these two determinations and the degree of filling of mortar in the grouted bolts (Zhong 1988, 1993). From the data presented it can be seen that the determined degrees of mortar filling conform completely to actual conditions. The maximum error for determined depth of insertion of anchors was an acceptable level of 0.2 m.

Note

1 It was not possible to ascertain from the author the generic chemical nature of the additive, described as being of a "TS" type. Ed.

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Techniques for Reinforcement of the Maijishan Grottoes

Yi Wuzhi and Lang Xiangui

The Maijishan grottoes, located 45 km southeast of Tianshui, Gansu Province, is one of the most famous grotto sites in China. Dating from about 400 C.E., the site consists of 194 caves housing more than 7,800 sculptural objects and 1,000 m^2 of wall paintings. From late 1975 to early 1994, a joint project for the restoration and consolidation of these fragile grottoes was undertaken (see acknowledgments). Four different techniques were tested and applied at the site: rock bolting, grouting, structural support, and spraying of concrete on the rock surface to prevent weathering.

Geology, Geomorphology, and Deterioration of the Maijishan Grottoes

Shaped like a haystack, Maijishan mountain is 142 m high (Figs. 1, 2). The east, west, and south sides are barren and steep with a slope of 95°. The bedrock is exposed and the lower part of the cliff has talus deposits. The Maijishan stratum, of Upper Tertiary period, is a purplish and brick-red conglomerate interspersed with thin layers of sandstone and mudstone loosely cemented by fine red clay containing calcium and iron (Huang 1976).

The severe, extensive deterioration of the Maijishan caves is the result of weathering, cracks caused by stress relief, and seismic activity. Various types of damage include cracking, collapse, flaking, and spalling due to moisture seepage, and repeated excavation of grottoes, all of which have left the cliff surface with many weathered, overhanging rocks (State Cultural Relics Museum 1964).

Technical Research on Stabilization of the Grottoes

Based on the initial condition survey of the caves, the stabilization plan for the Maijishan grottoes was initiated in 1960. Various organizations, including the State Cultural Relics and Museum Institute, recommended reinforcement of the grottoes as the only way to preserve these cultural treasures. In 1974, after several years of extensive investigation, the Gansu Provincial Construction Survey and Design Bureau proposed the use of steel rock bolts and concrete retaining walls to reinforce the cliff on the

Figure 1
Maijishan grottoes after the 1984 stabilization.

Figure 2
An early view of the Maijishan grottoes.

west side and the use of steel-and-concrete frame structures to support the roof (Gansu Construction Survey 1975).

At the end of 1975, the authors conducted preliminary field testing of a rock bolting technique using steel and concrete grouting. The success of these trials demonstrated the possibility of designing a strategy employing new methods (Yi and Lang 1979). By the end of 1983, the team completed research, design, and application of the four techniques detailed below: sprayed concrete, rock bolting, grouting, and structural support.

Tests of sprayed concrete

To prevent further weathering of the poorly cemented conglomerate, concrete was sprayed on the surface of the rock. A pull test was performed on five of the areas treated. In all five cases, breakage occurred at the inner layer of the rock, not at the concrete-conglomerate interface, demonstrating that concrete adheres well to the conglomerate.

Tests of rock bolting

The main objective of this experiment was to fasten the fragile and precariously hanging cliff rocks to the firmer substrata with steel rock bolts. To ensure the safety of the cultural relics in and outside the caves, as well as of personnel, successful drilling, grouting, and bolt anchoring methods were essential. First, a series of holes, 12–60 mm in diameter, was drilled to a depth of 3–15 m using an electric rock drill with a guiding track. Techniques and equipment were also developed for bolting after grouting.

Two kinds of rock bolting tests were performed: (1) tensile strength of steel rods bolted and grouted into the cliff face, and (2) shear strength of the conglomerate with concrete grouting and steel rock bolts.

Sixty-six types of rods were tested in situ for their tensile strength. Commercial cement mortar and no. 16 manganese spiral steel, 16–32 mm in diameter, were found to provide a good anchoring effect. This steel anchor has a maximum tensile yield strength when the bolting length is twenty-five times the diameter of the rod. After unfavorable factors were taken into account, such as the property of the rock and the quality of grout filling, the bolting length was set at thirty to fifty times the rod diameter.

To obtain test results that approximated actual conditions, bolted and unbolted conglomerate blocks were comparison tested in situ (Fig. 3), with the bolted samples anchored directly to the cliff face with horizontal and inclined rods. A hydraulic jack was used to shear the blocks. Results were as follows:

First, both horizontal and inclined rods produced a remarkable improvement in the crack-resistance and ultimate-rupture loads of the conglomerate (Table 1). Blocks reinforced with two steel rods of 20 mm diameter showed average increases of 36% in crack-resistance load and 100% in ultimate-rupture load.

A second important effect of the steel-rod reinforcement was improvement in the sudden shear rupture characteristics of the conglomerate. Unbolted blocks ruptured under a 10 t load, whereas the bolted blocks only fractured. These tests indicated that bolted blocks can sustain 21–55% more load than unbolted blocks.

Bolting also increased the maximum shear displacement of the conglomerate. Tests found the shear displacement of the bolted blocks to be five to nine times that of the unbolted conglomerate before rupture.

In summary, conglomerate reinforced with steel rock bolts in combination with cement grouting showed higher tensile and shear strengths than unconsolidated conglomerate.

Tests of crack grouting

In 1983, Li Zuixiong successfully tested a high molar-ratio (K_2O:SiO_2) potassium silicate consolidant. Li and the authors studied the characteristics

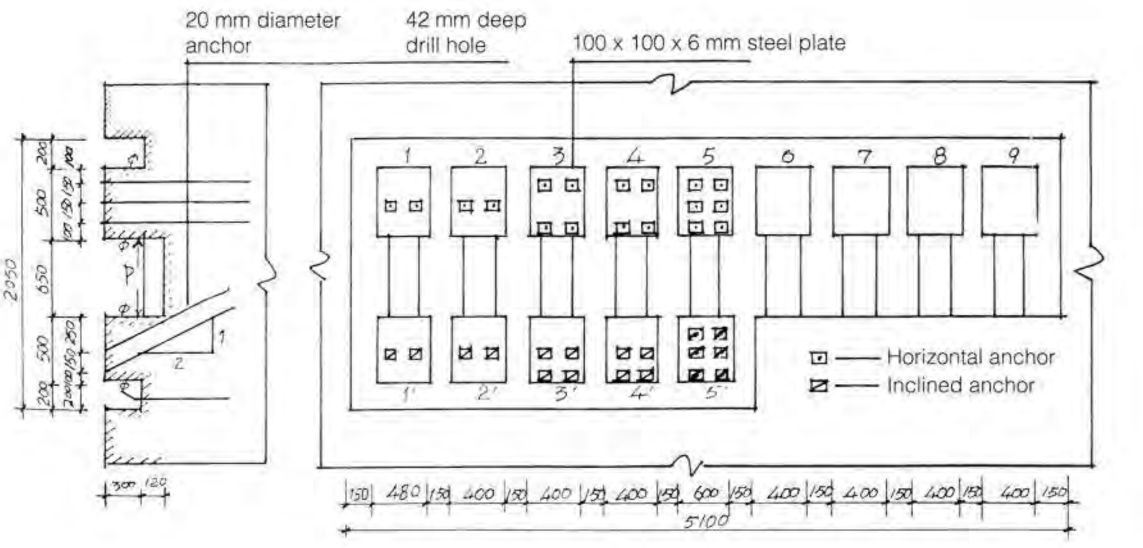

Figure 3
Plan of the shear testing site of the Maijishan conglomerate with and without anchor bolts.

Table 1 On-site shear tests of the conglomerate with and without anchors

Sample	Sample	Shear rupture		Maximum shear		Maximum		%		Fracture
Type	No.	Load N_T (kN)	Displacement ΔT (mm)	Load N_p (kN)	Displacement Δp (mm^2)	Shear Rt ($N\ mm^{-1}$)	Rt Rg^{-1}	N_T	N_p	Characteristics
Conglomerate	6	140	0.16	140	0.16					Brittle
Conglomerate	7	100	0.12	100	0.12					Brittle
Conglomerate	8	140		140				100	100	Brittle
Conglomerate	9	180	0.18	180	0.18					Brittle
with 2 20-mm HA[a]	1	200	0.37	280	1.77	445.8	1.29	143	200	3 mm shear fracture
with 2 20-mm HA	2	180	0.31	280	1.66	445.8	1.29	129	200	3 mm shear fracture
with 4 20-mm HA	3	280	0.38	340	1.57	270.7	0.783	200	242	2.5–4 mm shear and tension cracks
with 4 20-mm HA	4	280	0.39	350	1.01	278.6	0.808	200	250	2.5–4 mm shear and tension cracks
with 6 20-mm HA	5	280	0.47	355	1.04	188.4	0.545	200	253	3 mm shear and tension cracks
with 6 20-mm HA	5′	280	0.51	350		185.7	0.537	200	250	3 mm shear and tension cracks
with 2 20-mm IA[b]	1′	320	0.29	>360				228	>257	2 mm shear fracture
with 2 20-mm IA	2′	320	0.45	420	1.65	598.0	1.730	228	300	2 mm shear fracture
with 4 20-mm IA	4′	380	0.505	>500		>356		271	>357	

[a] HA = horizontal anchors

[b] IA = inclined anchors

and application of potassium silicate mixed with the fine red clay of the Maijishan conglomerate to form a composite for grouting crevices (Li and Yi 1983).

Research on the Maijishan cliff showed that the strength of the potassium silicate consolidant and that of the composite with red clay were clearly greater than that of the conglomerate. Tests of conglomerate rock cemented by potassium silicate and by the composite indicated much greater tensile strength than that of similar test pieces grouted with a high-polymer emulsion or epoxy resin. Because the potassium silicate component was able to penetrate into and solidify the strength of the clay, the two potassium silicate–based mortars not only filled the cracks of the Maijishan conglomerate to which it was applied but also penetrated and consolidated the surrounding rock.

These results provided the basis for the design and application of the consolidation plan for the Maijishan grotto site.

Structural Stabilization Techniques

In addition to repairing and maintaining the temples, pavilions, and other structures, the restoration of the Maijishan grottoes focused on the strengthening of the cliff face and construction of new wooden walkways (Yi 1984). Techniques of rock bolting, grouting, and surface spraying with

concrete, with the addition of structural supports, were applied to stabilize the cliff face, as follows:

Sprayed concrete

Concrete was sprayed onto the cliff face with and without the installation of a 6–8 mm diameter steel reinforcing net laid on the surface. These two types of operations had four purposes: (1) to fill all the crevices, (2) to protect the cliff face from further weathering, (3) to stabilize dangerous rocks, and (4) to restore the cliff face and eaves of the corridors.

High-pressure spraying of concrete was used to fill more than a thousand small holes created by water erosion and old walkway posts, and large crevices on the cliff face of the grottoes. The holes ranged from 20 to 30 cm in diameter and were about 50–60 cm deep.

To provide protection from further erosion, the cliff face was sprayed with concrete over a steel reinforcement net. This has been shown to effectively slow weathering. Sprayed concrete has also effectively limited the displacement of the surrounding rock, thus preventing the loosening, spalling, and collapse. This technique was employed as a preliminary, immediate measure for the stabilization of the strata.

Because concrete sprayed under high pressure can reach a thickness of 10–15 cm, collapsed bedrock on the cliff face, corridors, and eaves could also be restored to their original shapes by applying the concrete over a steel reinforcement net in combination with rock bolting.

Rock bolting and grouting

For further structural reinforcement, mortar was used in combination with spiral steel bolting rods to fasten layers of fractured or earthquake-damaged rocks onto the more stable substrata. Cracks inside the caves were treated with sealing and grouting methods, according to their individual condition. Potassium silicate and the added clay composite were used for this purpose.

Structural support

In addition to spraying concrete, rock bolting, and grouting, a steel-and-concrete structure was built to support the huge unstable roof rock between the Seven Buddha pagoda and Niuer Tang (hall). The structure is 1.5 m thick, 3.5 m high, and 3.5 m wide. Six steel rods 32 mm in diameter, spaced 700 mm apart, were horizontally anchored 6 m deep into the bedrock. In addition, several steel rods were obliquely anchored 15 m deep.

Characteristics of structural stabilization techniques

Compared with the previous reinforcement method of retaining pillars, the new techniques of concrete spraying, rock bolting, grouting, and structural support used at the Maijishan grottoes demonstrated a range of valuable characteristics, as follows:

1. Thinness: The retaining pillars, which are about 0.5–10 m thick, were reinforced by spraying concrete and rock bolting. When steel bolts 3–15 m long were used to anchor the fractured rocks, a concrete coating with a thickness of only 50–150 mm was needed.
2. Firmness: Steel bolts 3–15 m in length used to strengthen the cliff face effectively increased the internal strength of the rocks. These rods function like ribs in a body.
3. Depth: Steel rods anchored deep into bedrock remarkably increased the cohesion and stability of the rock.
4. Adaptability: In addition to strengthening, these techniques can also be applied to the restoration of the site (collapsed bedrock, corridors, and eaves).
5. Speed: High-speed, high-efficiency electric machines were used to carry out drilling, grouting, and spraying.
6. Economy: Much less material was needed for this design when compared to that of the construction of a typical retaining pillar.
7. Aesthetics: An appropriate amount of red clay was added to the concrete coating to match the original surface color. Thus, steel rods anchored into the rocks do not affect the appearance of the grottoes or the cliff face.

Conclusions

In a 1984 evaluation, conservation experts and scholars stated, "Loosely cemented conglomerate, the steep slope, and the huge rocks hanging inside the caves have made the consolidation of the Maijishan grottoes a difficult and dangerous operation" (Yi and Lang 1984).

The present comprehensive approach to the consolidation of the Maijishan grottoes—concrete spraying, grouting, rock bolting, and construction of a structural support—all without substantially changing the appearance of the caves, has opened a new avenue for the conservation of grotto sites (Figs. 4, 5). This is an outstanding example of how advanced technology can be applied in the protection of threatened cultural heritage.

Acknowledgments

The research, design, and implementation of this project were carried out under the guidance of the State Bureau of Cultural Relics, the State Cultural Relics Museum and Research Institute, and the Gansu Provincial Culture Department from the end of 1975 to the beginning of 1994. This is a joint effort among specialists from the Gansu Provincial Architecture Institute; the Gansu Construction Survey and Design Institute; the Fifth Construction Engineering Company; and the Maijishan Consolidation Office, a temporary office in charge of project design and supervision. The authors would like to take this opportunity to express their sincere gratitude to the leading officers, experts, and all the engineering crew members who assisted in this project.

Figure 4
An early view of Maijishan Grotto 15 to the fifth section.

Figure 5
Grotto 15 to the fifth section after stabilization.

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Chemical Consolidation of Conglomerate and Sand at the Mogao Grottoes

Li Zuixiong, Neville Agnew, and Po-Ming Lin

Figure 1
Gravel plateau above the Mogao grottoes, connected to the Mingsha mountain in the west. A windbreak fence was built in front of the mountain.

THE MOGAO GROTTOES were excavated in a north-south-oriented cliff face on the west bank of the Daquan River. The cliff face is 1,680 m long and approximately 20 m high. At the base of the cliff is a relatively flat sand-and-gravel ground. The cliff is about 90 m at its closest point to the Daquan River and about 180 m at the farthest point from it. Trees have been planted on the flat, elongated area in front of the cliff. The caves are excavated in the south 1,000 m of the cliff face. In the northern area, except for a few caves that are decorated with murals and polychrome statues, most of the caves are undecorated and served as living quarters for craftsmen, monks, and pilgrims. Toward the top of the cliff in the southern region is a 35° erosional slope 30 m in width partly covered in sand and gravel with exposed surfaces of conglomerate. At the top of the slope is a 3,000 × 800 m plateau composed of sand and gravel, leading to the Mingsha mountain in the west (Fig. 1).

This region is characterized by large sand dunes, and winds blow from several directions seasonally. The westerly winds bring sand from the dunes of the Mingsha mountain, causing erosion of the cliff rock and damage to the grotto areas.

On the basis of estimates, 3,000 m^3 of sand accumulated annually in front of the cliff face before the installation of the windbreak fence. The sand blocked walkways and entrance doors, and fine dust infiltrated the grottoes, settling on the statuary and wall paintings. Removal of such a large sand accumulation required considerable annual expenditures of money.

A knitted synthetic fabric windbreak fence in an A shape (as viewed from above) was installed on the top of the cliff to control the windblown sand carried by the westerly winds. The apex of the triangular windbreak fence is about 70 m from the Mingsha mountain and is pointed toward it; its base is about 800 m in length. It is parallel to the cliff face and positioned about 200 m from it. All the southern caves are enclosed in the area protected by it (Fig. 2).

Since its erection, the windbreak fence has effectively prevented sand blowing from the Mingsha mountain from entering the grotto area.

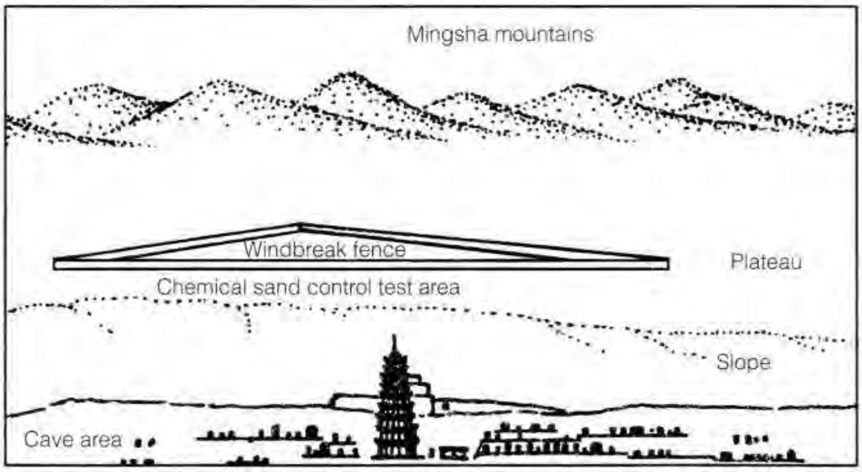


Figure 2
Schematic drawing showing the locations of the A-shaped windbreak fence and chemical consolidation test area.

This has resulted in the sand carried by the wind being deposited around the windbreak fence or diverted to outside the grotto area, thus reducing the sand deposit in the grotto area by 60%. However, since the installation of the windbreak fence, the balance of supply of sand to the cliff face has been disturbed. Wind has stripped the 30° slope and plateau behind it of its residual sand, exposing the weak conglomerate of the cliff to more rapid erosion than it experienced previously (Fig. 3). Analysis of the sand grains collected from sand traps placed on the walkways and around the grotto area shows that after the installation of the windbreak fence, coarser sand grains and even pebbles were deposited (Ling et al. 1993). The upper layers of the Quaternary argillaceous conglomerate cliff rock are loosely cemented and easily eroded by wind, causing pebbles to fall from the top of the cliff. This is not only dangerous to pedestrians on the walkways below, but thinning of the rock of the roofs of some of the upper-level caves—a phenomenon already well advanced—will further endanger these caves. It is presently considered that it will probably be necessary to chemically consolidate the sand in front of the windbreak fence, and the exposed rock of the cliff slope. In fact, the latter is the principal objective of the testing described in the present paper because of the ease of erosion of the exposed rock on the 30° slope. With the installation of the windbreak fence completed, testing of chemical consolidation became the next priority, the use of both the windbreak fence and chemical consolidation being planned as a comprehensive sand-control system.

Figure 3
Severely eroded strata at the Mogao grottoes.

Experimental Work

Sand sample analysis

Analysis of sand granularity

Sand samples were collected for analysis from three sites. Two samples collected from the chemical consolidation test area located east of the windbreak fence were a mixture of coarse sand, gravel, and clay. The third sample, collected on the slope north of the Nine-Story Pagoda, consisted

of homogeneous, fine-grained sand. The fourth sample, collected from the sand deposited along the shelter north of the Nine-Story Pagoda, was also fine and homogeneous. Results are presented in Table 1.

Mineralogical analysis of sand samples

The sand samples for mineralogical analysis were collected from the chemical consolidation test area on the eastern side of the windbreak fence. Results are given in Table 2.

Consolidants tested

Two types of binding agents, an inorganic one and synthetic organic polymers, were used for chemical consolidation tests on the top of the cliff of the Mogao grottoes. The inorganic material was a high-molar potassium silicate (PS)[1] (Li 1985; Nishiura and Li 1988). Three types of organics were used: (1) Primal AC-33, an aqueous emulsion composed of 40% methacrylates and 60% acrylates (abbreviated AC); (2) a polyvinyl acetate emulsion, Aerospray 70 Binder (abbreviated AS); and (3) a mixture composed of copolymer of methacrylates and acrylate (40%), polyethoxylated ethanol (1%), silicates (3.5%), 12.3% polymethacrylates, 42% acrylates, and 1% organic silicate emulsion, to which 0.2% polyethoxylated ethanol was also added; it is commonly called Soil Seal (abbreviated SS).

Determination of the permeation of consolidants on sand

Two types of sand were selected to test the depth of penetration of consolidants. One was from the chemical consolidation area on the eastern side of the windbreak fence (designated A), the other was from the fine-grained deposit on the north side of the Nine-Story Pagoda (designated B). Samples were introduced into transparent cylindrical tubes (45 × 300 mm). Samples were packed by the same method so that the compaction would be essentially similar. Consolidants were diluted to suitable concentrations and dripped onto the top of the samples at the same speed; the permeation rates were recorded (Fig. 4; Table 3).

Figure 4
Sand samples for consolidant permeation test (45 × 300 mm).

Determination of the water-absorption capacity of consolidated sand samples

Determinations were made according to standard methods for rock in which a cylindrical sample (50 × 100 mm) is soaked in water for forty-eight hours and reweighed. It is important that water be able to pass quickly through the consolidated sand and rock covering the cliff top and the slope of the Mogao grottoes; if the consolidated sand has a very low water permeability, most of the rainwater will not be able to permeate the sand and will collect and run down the slope, accelerating erosion and possibly endangering the grottoes over time.

A mold was made, and the sand from groups A and B were made into cylindrical samples 50 mm in diameter and 100 mm in height. Three samples from each group were consolidated using 1:10 water solutions of

Table 1 Sand granularity analysis: particle size and percentage

	Sample no. 1	Sample no. 2	Sample no. 3	Sample no. 4
Mean size (mm)	Percentage	Percentage	Percentage	Percentage
15.0	5.32			
10.0	2.21	2.18		
7.00	2.35	9.09		
4.00	3.78	11.45		
2.00	4.89	15.12		
1.00	6.15	15.35		
0.50	2.24	1.85	0.90	1.32
0.40	1.05	0.43	3.75	1.03
0.315	2.31	0.94	10.82	2.57
0.25	5.13	2.64	20.53	6.60
0.200	2.16	1.33	4.42	1.73
0.160	8.23	3.91	17.86	8.45
0.125	14.88	9.02	23.34	28.08
0.10	12.58	8.55	10.98	23.23
0.08	7.2	4.62	3.32	8.74
0.063	11.84	8.52	3.26	13.76
<0.063	7.68	5.00	0.82	4.50

Sample 1 collected from 2 to 5 cm depth at the chemical consolidation test site, east of the windbreak fence.

Sample 2 collected from the surface 0 to 2 cm at the chemical consolidation test site, east of the windbreak fence.

Sample 3 collected from the surface north of the Nine-Story Pagoda.

Sample 4 collected from the slope surface north of the Nine-Story Pagoda.

Table 2 Petrological analysis of the sand

Heavy minerals (Density > 2.85)								Light minerals (Density < 2.85)	
Unstable minerals		Relatively stable minerals		Stable minerals		Very stable minerals		quartz	46.50
augite	7.00	diopside	10.00	black metal ore	6.00	limonite	3.50	orthoclase	6.25
enstatite	1.00	tremolite	4.50	titanite	0.25	leucoxene	1.50	plagioclase	19.00
hornblende	47.00	actinolite	1.00			zircon	0.50	weathered plagioclase	6.00
grunerite	2.00	epidote	4.75			tourmaline	0.75	chalcedony	0.25
lamprobolite (basaltic hornblende)	0.75	zoisite	0.75			limonite	7.50	carbonates	1.50
		allanite	0.50					rock debris	20.50
		chlorite	0.75						
Subtotal	57.75	Subtotal	22.25	Subtotal	6.25	Subtotal	13.75	Total	100.00

Table 3 Permeation tests on sand

Sample no.	Consolidant	Concentration (in water)	Permeation depth/time	Total volume (ml)	Time (minutes)[a]
A-1	AC	1:10	9 cm / 10 min	250	50
A-2	AS	1:10	9 cm / 10 min	200	70
A-3	SS	1:10	11 cm / 10 min	215	45
A-4	PS	10%	7 cm / 10 min	200	50
B-1	AC	1:10	13 cm / 5 min	210	30
B-2	AS	1:10	13 cm / 5 min	250	20
B-3	SS	1:10	12 cm / 5 min	250	45
B-4	PS	10%	12 cm / 5 min	250	20

[a] Time required for consolidant to penetrate the entire sample

AC, AS, or SS, and PS at a concentration of 10% in water (Fig. 5). After curing, water absorption tests were carried out. Results are given in Table 4 (Figs. 6, 7).

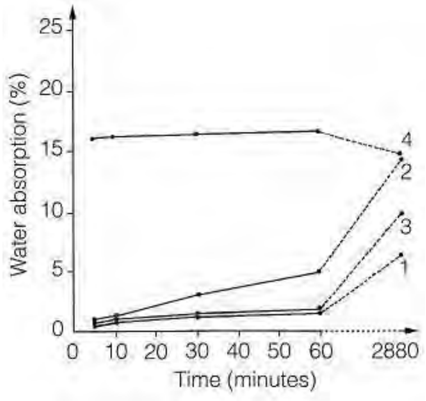
Figure 5
Sand samples for water absorption test (50 × 100 mm).

Table 4 Water absorption test of consolidated sand samples (continued on next page)

Sample no.		Cons.	Conc.	Dry wt. (g)	Wet wt. 5 min (g)	A.W.[a] (g)	A.R.[b] (%)	Wet wt. 10 min (g)
	1	AC	1:10	362.00	362.80	0.80		363.90
A-1	2	AC	1:10	369.00	371.20	2.20	0.39	372.70
	3	AC	1:10	360.30	361.70	1.40		362.50
	1	AS	1:10	382.00	384.20	2.20		387.50
A-2	2	AS	1:10	364.00	366.50	2.50	0.81	370.05
	3	AS	1:10	365.70	370.01	4.31		372.90
	1	SS	1:10	353.00	354.50	1.50		356.00
A-3	2	SS	1:10	356.50	357.90	1.40	0.38	359.00
	3	SS	1:10	369.30	370.50	1.20		372.20
	1	PS	10%	313.50	367.00	53.50		368.00
A-4	2	PS	1:10	314.10	369.00	54.90	16.38	369.40
	3	PS	1:10	329.00	377.00	48.00		378.00
	1	AC	1:10	317.50	321.40	3.90		322.30
B-1	2	AC	1:10	310.00	313.50	3.50	1.33	315.00
	3	AC	1:10	307.60	312.30	4.70		314.00
	1	AS	1:10	303.50	321.50	18.00		328.00
B-2	2	AS	1:10	312.00	334.10	22.10	5.86	339.50
	3	AS	1:10	328.00	343.00	15.00		352.50
	1	SS	1:10	321.80	331.70	9.90		337.30
B-3	2	SS	1:10	323.20	327.10	4.00	2.54	335.50
	3	SS	1:10	323.20	334.00	10.80		348.50
	1	PS	10%	339.80	386.70	46.90		390.50
B-4	2	PS	1:10	323.30	365.50	42.20	13.06	375.20
	3	PS	1:10	338.00	379.70	41.70		384.00

[a] A. W. = weight of absorbed water

[b] A. R. = water absorption rate



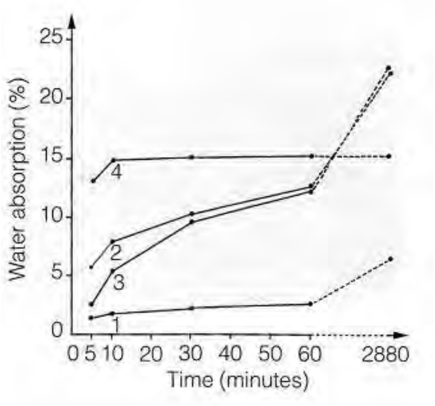


Figure 6
Water absorption of consolidated group A sand: 1 = AC; 2 = AS; 3 = SS; 4 = PS.

Figure 7
Water absorption of consolidated group B sand: 1 = AC; 2 = AS; 3 = SS; 4 = PS.

Determination of the compressive strength of consolidated rock

Rock collected from severely weathered areas in the northern region of the Mogao grottoes was made into 50 × 50 × 50 mm samples (Fig. 8).[2]

Table 4 continued

Sample no.		A.W. (g)	A.R. (%)	Wet wt. 30 min (g)	A.W. (g)	A.R. (%)	Wet wt. 1 hr (g)	A.W. (g)	A.R. (%)	Wet wt. 48 hrs (g)	A.W. (g)	A.R. (%)
	1	1.90		364.30	2.30		365.30	3.30		380.50	18.50	
A-1	2	3.70	0.71	374.50	5.50	1.04	376.50	7.50	1.46	399.50	30.50	6.88
	3	2.20		364.00	3.70		365.50	5.20		386.50	26.20	
	1	5.50		393.00	9.00		400.00	18.00		437.00	55.00	
A-2	2	6.05	1.69	376.00	12.00	2.91	384.50	20.50	4.94	414.30	50.30	14.34
	3	7.20		377.00	11.30		382.10	16.40		419.80	54.10	
	1	3.00		357.50	4.50		359.30	6.30		389.20	36.20	
A-3	2	2.50	0.78	360.00	3.50	1.13	362.10	5.60	1.65	390.50	34.00	9.86
	3	2.90		373.50	4.20		375.20	5.90		405.50	36.20	
	1	54.50		368.50	55.00		368.50	55.00		373.00	30.60	
A-4	2	55.30	16.62	369.70	55.60	16.71	369.70	55.60	16.76	373.50	59.40	16.97
	3	49.00		378.30	49.00		378.50	49.50		382.50	53.50	
	1	4.80		324.00	6.50		325.00	7.50		337.30	19.80	
B-1	2	5.00	1.73	316.20	6.20	2.20	317.00	7.00	2.50	326.90	16.90	6.32
	3	6.40		315.50	7.90		316.50	8.90		330.00	22.40	
	1	24.50		335.00	31.50		340.00	36.50		369.50	66.00	
B-2	2	27.50	8.11	346.90	34.90	10.26	353.30	41.30	12.54	383.00	71.00	22.09
	3	24.50		361.90	33.90		368.50	40.5		399.40	71.40	
	1	15.50		346.00	24.20		350.00	28.20		383.20	61.40	
B-3	2	12.30	5.48	355.20	32.00	9.65	370.00	46.80	12.34	396.20	73.00	22.43
	3	24.30		360.50	37.30		367.80	44.60		406.00	82.80	
	1	50.70		391.20	51.40		391.20	51.40		391.00	51.20	
B-4	2	51.90	14.86	376.20	52.90	15.03	376.80	53.50	15.14	377.00	53.90	15.56
	3	46.00		384.00	46.00		384.50	46.50		388.50	50.50	

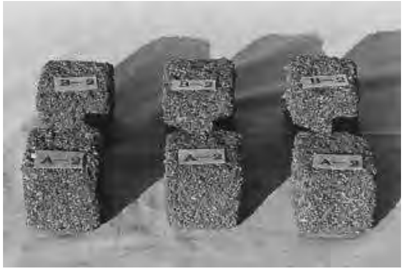


Figure 8
Consolidated rock samples prepared for property tests (50 × 50 × 50 mm).

The samples were permeated and consolidated with AC, AS, and SS in concentrations of 1:10 (water) and with 10% PS. Because the cliff rock is poorly cemented conglomerate of low strength, the permeation and consolidation of the samples was carried out in several steps to avoid disintegration in water. In the first step, only a small amount of consolidant was added. The second and third steps were not carried out until the samples were completely dried, and were continued until the samples were completely saturated. Compressive strength was determined using a Newton hydraulic universal testing machine (model WE-10A, 1004). Test results are given in Table 5.

In addition, the compressive strength of consolidated sand was determined. Samples of the same size were treated similarly to the rock samples in preparation for testing. Results are given in Table 6.

Wind-tunnel erosion tests on cliff conglomerate

Samples of approximately 50 × 50 × 50 mm were taken from weathered rock from the northern region of the grottoes. Samples were consolidated using AC, AS, and SS in concentrations of 1:10 (water), and with 10% PS, as previously.

Table 5 Compressive strength of consolidated weathered rock

Sample no.	Consolidant	Load (kN) 1	2	3	4	5	Average	Compressive strength (MPa)	Note
A_0 1–5	—	0.50	0.45	0.20	0.10	0.35	0.32	0.13	Unconsolidated
A 1–3	AC 1:10 (water)	9.20	10.20	14.10			11.17	4.47	Consolidated
B 1–3	AS 1:10 (water)	3.50	6.70	2.20			4.13	1.65	Consolidated
C 1–3	SS 1:10 (water)	1.35	3.00	1.00			1.78	0.17	Consolidated
D 1–3	PS 10%	31.50	29.00	32.30			30.93	12.37	Consolidated

Table 6 Compressive strength of consolidated cylindrical sand (50 × 50 mm cross section)

Sample no.	Consolidant	Load (kN) 1	2	3	Average	Compressive strength (MPa)
A-1	AC 1:10 (water)	3.90	2.30	3.20	3.13	1.20
B-1	AC 1:10 (water)	1.50	1.60	1.30	1.47	0.60
A-2	AS 1:10 (water)	10.60	15.90	13.80	13.43	5.40
B-2	AS 1:10 (water)	1.50	1.80	0.90	1.40	0.60
A-3	SS 1:10 (water)	1.40	1.70	1.20	1.43	0.60
B-3	SS 1:10 (water)	1.20	1.00	1.20	1.13	0.40
A-4	PS 10%	16.70	17.60	31.00	21.77	8.70
B-4	PS 10%	19.10	10.90	6.70	12.23	4.90

The wind-tunnel simulation tests of wind erosion were carried out at the Desert Research Institute of the Chinese Academy of Sciences in Lanzhou. The wind tunnel is 38.78 m in length, the testing segment length being 16.23 m with a cross-sectional area of 1×0.6 m^2. Wind speed is continuously adjustable from 2 to 35 m s^{-1}, and turbulence intensity is below 0.4%. During the test, samples were set horizontally on sample trays capable of being elevated to any desired position. Samples were placed 12 m from the entrance of the tunnel in the wind direction. Test results are shown in Table 7 (Figs. 9, 10).

Freeze-thaw tests of consolidated rock samples

Rock samples similar to those used in previous tests were used for freeze-thaw tests. Because of the high porosity and high water absorption of the conglomerate, the samples disintegrated easily when frozen and thawed. The conditions of the samples in different freeze-thaw cycles were recorded, but the weight losses were not recorded. Testing was continued until all the samples had disintegrated. The number of freeze-thaw cycles was recorded, and rough estimates were made of the resistance to freezing and thawing of the weathered rock samples and the samples after consolidation.

Freeze-thaw tests were performed on four groups of samples (three samples in each group) after consolidation using AC, AS, and SS at concentrations of 1:10 (water), and of 10% PS. Samples were first heated at 105–110 °C to constant weight, after which they were soaked in water at 20 °C for four hours. They were then placed in a freezer at −30 °C for four hours. Repeated cycles of freezing and thawing consisted of thawing for four hours (20 °C water) and freezing for four hours (−30 °C), with each eight-hour period being counted as one cycle.

A minute crack developed in one of the 10% PS–consolidated samples in the third freeze-thaw cycle, at which time the other two samples were still intact. In the fifth freeze-thaw cycle, minute cracks also appeared in the other two. In the eleventh freeze-thaw cycle, there was expansion of the cracks in all three. During the seventeenth cycle, the corners of two of the samples fell off. During the twenty-eighth cycle, the two samples with chipped corners broke into two or three pieces. By the forty-fifth freeze-thaw cycle, all three rock samples virtually disintegrated.

One of the samples treated with AS developed a crack in the eighth cycle, at which time the other two samples were essentially intact. In the twelfth cycle, the crack that had already appeared expanded, a small piece broke off from the lower part of the second sample, and a minute crack also developed in the third rock sample. By the forty-fifth freeze-thaw cycle, there was clear enlargement of the cracks in all three rock samples. However, there was no evidence of disintegration.

The corners of one of the AC samples broke off at the twentieth freeze-thaw cycle. The other two samples were basically intact. In the twenty-sixth cycle, there was disintegration of the lower portion, whereas there were no changes in the other two samples. During the thirty-third cycle, distinct cracks appeared in the sample that had begun to disintegrate, and the corners fell off of the other two samples, which also showed

Table 7 Wind-tunnel erosion experiments on consolidated cliff conglomerate

Sample no.	Consolidant	Surface area (cm^2)	Duration (minutes)	Wind vel. ($m\ s^{-1}$)	Sample wt. before (g)	Sample wt. after (g)	Weight loss (g)	Calculated weight loss ($kg\ m^{-2}\ hr^{-1}$)	Notes
A_0	untreated control	48.1	30	5	896.0	896.0	0		
A_0	untreated control	48.1	30	10	896.0	893.5	2.5[a]		Wind only
A_0	untreated control	48.1	30	15	893.5	893.0	0.5	0.21	
A_0	untreated control	48.1	15	20	893.5	892.5	1.0	0.21	
A_0	untreated control	48.1	30	7	892.5	881.0	11.5	4.78	Wind and sand (threshold vel. 6.2 $m\ s^{-1}$)
A_0	untreated control	48.1	20	10	881.0	682.5	198.5	123.80	
A_0	untreated control	48.1	6	15	682.5	436.5	246.0	512.47	
A_0	untreated control	54.6	3	20	809.5	241.3	568.2	2081.32	
A_1	AC 1:10	56.5	30	5	933.5	933.5	0		
A_1	AC 1:10	56.5	30	10	933.5	933.5	0		Wind only
A_1	AC 1:10	56.5	30	15	933.5	933.5	0		
A_1	AC 1:10	56.5	15	20	933.5	933.5	0		
A_1	AC 1:10	56.5	30	7	933.5	933.0	0.5	0.18	Wind and sand (threshold vel. 6.2 $m\ s^{-1}$)
A_1	AC 1:10	56.5	20	10	933.0	932.0	1.0	0.53	
A_1	AC 1:10	56.5	6	15	932.0	931.0	1.0	1.77	
A_1	AC 1:10	56.5	3	20	931.0	928.5	2.5	10.62	Wind only
A_2	AS 1:10	58.9	30	10	948.0	948.0	0		
A_2	AS 1:10	58.9	30	20	948.0	948.0	0		
A_2	AS 1:10	58.9	30	7	948.0	948.0	0		
A_2	AS 1:10	58.9	20	10	948.0	947.0	1.0	0.51	Wind and sand
A_2	AS 1:10	58.9	11	15	947.0	945.5	1.5	1.39	
A_2	AS 1:10	58.9	7	17	945.5	943.0	2.5	3.64	
A_2	AS 1:10	58.9	8	20	943.0	936.0	7.0	8.91	
A_3	SS 1:10	57.3	30	10	902.0	902.0	0		Wind only
A_3	SS 1:10	57.3	30	20	902.0	902.0	0		
A_3	SS 1:10	57.3	30	7	902.0	902.0	0		
A_3	SS 1:10	57.3	20	10	902.0	902.0	0	0.52	
A_3	SS 1:10	57.3	11	15	901.0	901.0	0		Wind and sand
A_3	SS 1:10	57.3	7	17	901.0	900.0	1.0[a]	0.52	
A_3	SS 1:10	57.3	8	20	900.0	900.0	0		
A_4	PS 10%	52.0	30	5	917.5	917.5	0		
A_4	PS 10%	52.0	30	10	917.5	917.5	0		Wind only
A_4	PS 10%	52.0	30	15	917.5	917.5	0		
A_4	PS 10%	52.0	15	20	917.5	917.5	0		
A_4	PS 10%	52.0	30	7	917.5	916.7	0.8	0.31	Wind and sand (threshold vel. 6.2 $m\ s^{-1}$)
A_4	PS 10%	52.0	20	10	916.7	916.7	0		
A_4	PS 10%	52.0	6	15	916.7	916.5	0.2	0.38	
A_4	PS 10%	52.0	3	20	916.5	916.5	0		

[a] possible error in measurement

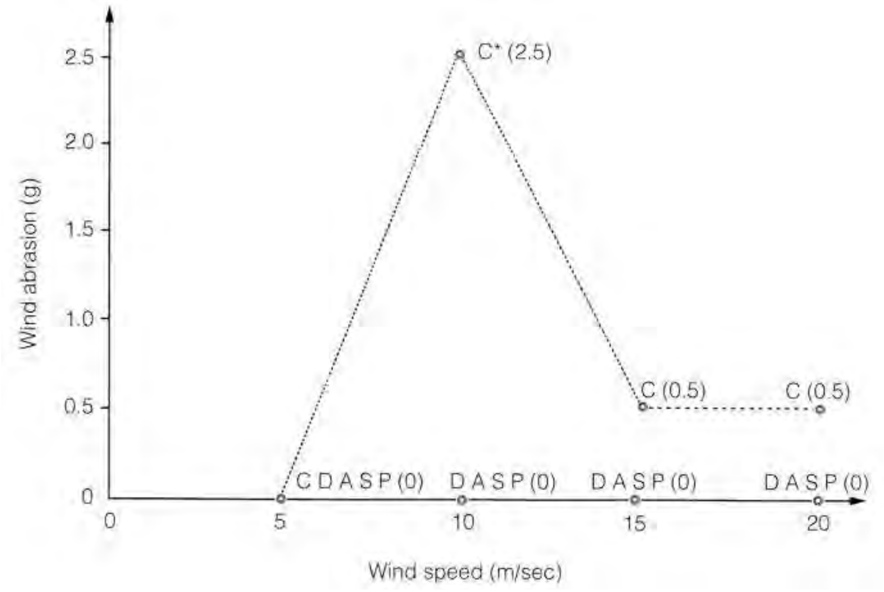


Figure 9
Abrasion loss of consolidated rock sample in the wind tunnel test (wind only): C = unconsolidated; D = AC; A = AS; S = SS; P = PS.

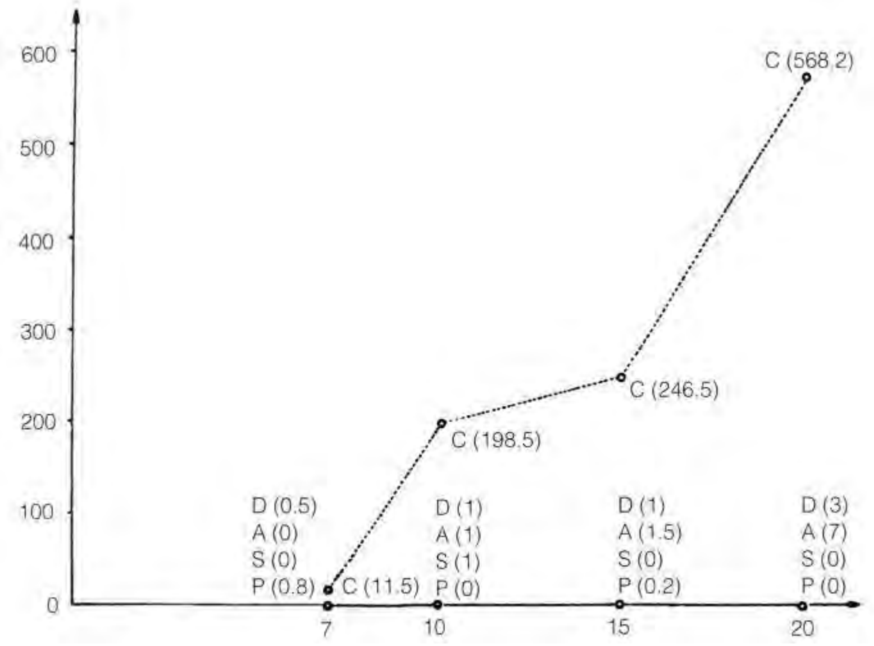


Figure 10
Abrasion loss of consolidated rock sample in the wind tunnel test (wind plus sand): C = unconsolidated; D = AC; A = AS; S = SS; P = PS.

some disintegration. By the forty-third freeze-thaw cycle, all three samples had basically disintegrated.

Water resistance of consolidated sand samples

The sand samples consolidated with AC, AS, and SS at a ratio of 1:10 (water), and 5% PS were soaked in water to determine their water resistance. The 5% PS–consolidated sand sample was soaked in water for as long as sixteen months with no sign of disintegration. The AC, AS, and SS consolidated samples all showed signs of disintegration after two weeks; after two to three months, all had swelled and softened.

On-site chemical consolidation tests

The natural conditions at the cliff top allowed on-site chemical consolidation tests to be performed on the sand-covered area east of the windbreak fence and 150 m from the cliff face. The covering sand here consists primarily of mixed coarse and fine sand, together with small amounts of gravel and clay, and was the same as the group A sand samples used in the permeation tests described above.

The test area was divided into 2 × 2 m squares, after which the solutions of AC, AS, SS, and PS were sprayed on the surface. The squares were treated in two ways. In one case, the consolidant was sprayed directly onto the dry sand; in the other, water was first sprayed onto the dry sand so as moisten it to a depth of about 1–2 cm, and the consolidant was then applied. The objective of this procedure was to ascertain whether premelting would be an advantageous procedure.

PS of high modulus has frequently been used in the past for consolidation of both weathered conglomerate and weathered adobe buildings with good protective effects. The general method was first to spray low concentrations of PS, with a second application after the first had dried. Consolidation by this method may be carried out three or four times or more with increasing concentration to a final one not exceeding 5%. The number of treatments is determined primarily by the porosity and the required consolidation strength. In this way, the depth of penetration of consolidant is maximized. If the conglomerate or other rock is of very high porosity, the final PS spray concentration may be as high as 10%. In this test, the PS concentration was 5% and the spray volume was controlled at 2, 4, and 6 l m^{-2}.

Consolidation tests using an adhesive made by mixing potassium silicate and sodium silicate (abbreviated NaS) in 3:1 ratio were also performed. Results are presented in Table 8.

Three concentrations of AC were used in conducting on-site spraying and consolidation tests. Specifically, AC:water ratios of 1:10, 1:20, and 1:30 were used. Volumes used were 1.15, 2.30, 3.45, 4.60, and 5.75 l m^{-2} (Table 9).

The concentrations of AS and SS were the same as the AC concentrations, i.e., 1:10, 1:20, and 1:30. The spray volumes of AS were 4.60 and 5.75 l m^{-2}, and the spray volumes of SS were 2.30, 3.45, 4.60, and 5.75 l m^{-2} (Tables 10 and 11).

Hardness tests of consolidated sand

Six months after consolidation, surface hardness tests of the consolidated sand were carried out. At present, there is no standard method of performing surface hardness tests of consolidated sand. We used a simple puncture method and the resilience method with a Schmidt hammer to conduct comparative tests.

The puncture test used a steel pipe 2 cm in diameter and 111 cm in length, to which a sharp-tipped steel head had been attached, and mass

612.5 g. As shown in Figure 6, the steel pipe was held vertically and dropped from a height to the tip of 60 cm. The depth of penetration was measured. Three determinations were made on each test square. Results are given in Tables 8–11 and in Figure 11.

The Schmidt hammer (Chinese HT-225 "resilience meter"), the surface hardness meter most widely used at present, was used on the consolidated sand. Its impact kinetic energy is 0.225 kg·m, and it is commonly used to test concrete. As stated above, there is no standard method for determining the surface hardness of consolidated sand, and the Schmidt hammer tests were performed for reference purposes. For this reason, when the determinations were made on the test squares, the maximum and minimum resilience values were eliminated and the six most frequent resilience values taken. These values were not used for calculating hardness; rather, the aforementioned four types of consolidated sand were compared on the basis of the resilience values, after which the hardness of the consolidant surface was compared.

Determination of the penetration depth of the consolidant

The depth to which the consolidant penetrated was roughly estimated after completely drying by removing a block of consolidated sand and measuring its thickness. In part because spraying was done by hand, the depth of penetration was not uniform. Three points were selected for each test square for measurement of penetration depth. Results are given in Tables 8–11 and Figure 12.

Table 8 On-site sand consolidation test

Sample no.	Consolidant	Conc. (%) (in water)	Quantity ($l\ m^{-2}$)	Thickness of wetted sand layer (mm)	Average penetration (mm)	Puncture test averages (mm)	Schmidt hammer test averages (mm)	Appearance after one year
PS-1		5	6	1	40	2	11	No visible change
PS-2		5	4	1	32	5	11	
PS-3	PS	5	2	1	15	41	No rebound	
PS-4	(molar ratio	5	6	0	33	6	11	
PS-5	= 3.6)	5	4	0	21	18	No rebound	
PS-6		5	2	0	12	18	No rebound	
PS–NaS-1		15	6	0	37	8	No rebound	Salt efflorescence on the surface
PS–NaS-2		15	4	0	33	11	No rebound	
PS–NaS-3		15	2	0	12	32	No rebound	
PS–NaS-4	PS:NaS	7	6	0	35	12	No rebound	
PS–NaS-5	(3:1)	7	4	0	32	29	No rebound	
PS–NaS-6		7	2	0	14	39	No rebound	
PS–NaS-7		3.5	6	0	40	14	No rebound	
PS–NaS-8		3.5	4	0	30	19	No rebound	
PS–NaS-9		3.5	2	0	20	36	No rebound	

Table 9 On-site AC consolidated sand test

Sample no.	Dilution	Quantity (l m^{-2})	Thickness of wetted sand layer (mm)	Average penetration (mm)	Puncture test averages (mm)	Schmidt hammer test averages (mm)	Appearance after one year
AC-1	1:30	5.75	0	10	30	No rebound	Consolidation darkened the sand slightly
AC-2	1:30	4.60	0	13	22	No rebound	
AC-3	1:30	3.45	0	13	28	No rebound	
AC-4	1:30	2.30	0	9	36	No rebound	
AC-5	1:30	1.15	0	5	41	No rebound	
AC-6	1:20	5.57	0	18	12	No rebound	
AC-7	1:10	5.75	0	33	8	No rebound	
AC-8	1:30	5.75	10	12	34	No rebound	
AC-9	1:30	4.60	10	18	16	No rebound	
AC-10	1:30	3.45	10	19	22	No rebound	
AC-11	1:30	2.30	10	15	32	No rebound	
AC-12	1:30	1.15	10	9	34	No rebound	
AC-13	1:20	5.57	10	20	11	No rebound	
AC-14	1:10	5.75	10	27	9	No rebound	
AC-15	1:30	5.75	20	10	24	No rebound	Consolidation darkened the sand slightly
AC-16	1:30	4.60	20	20	14	No rebound	
AC-17	1:30	3.45	20	20	20	No rebound	
AC-18	1:30	2.30	20	12	25	No rebound	
AC-19	1:30	1.15	20	10	43	No rebound	
AC-20	1:20	5.57	20	33	13	No rebound	
AC-21	1:10	5.75	20	33	8	No rebound	

Table 10 On-site AS consolidated sand test

Sample no.	Dilution	Quantity (l m^{-2})	Thickness of wetted sand layer (mm)	Average penetration (mm)	Puncture test averages (mm)	Schmidt hammer test averages (mm)	Appearance after one year
AS-1	1:30	5.75	0	25	8	10	Consolidation darkened the sand slightly
AS-2	1:30	4.60	0	18	26	No rebound	
AS-3	1:20	5.75	0	23	8	10	
AS-4	1:20	4.60	0	25	8	No rebound	
AS-5	1:10	5.75	0	22	7	11	
AS-6	1:10	4.60	0	21	9	No rebound	
AS-7	1:30	5.75	10	23	14	No rebound	Consolidation darkened the sand slightly
AS-8	1:30	4.60	10	23	11	No rebound	
AS-9	1:20	5.75	10	23	7	10	
AS-10	1:20	4.60	10	27	6	10	
AS-11	1:10	5.75	10	27	3	11	
AS-12	1:10	4.60	10	23	10	10	
AS-13	1:30	5.75	20	25	7	10	Consolidation darkened the sand slightly
AS-14	1:30	4.60	20	23	20	No rebound	
AS-15	1:20	5.75	20	23	8	11	
AS-16	1:20	4.60	20	23	19	No rebound	
AS-17	1:10	5.75	20	33	6	11	

Table 11 On-site SS consolidated sand test

Sample no.	Dilution	Quantity (l m^{-2})	Thickness of wetted sand layer (mm)	Average penetration (mm)	Puncture test averages (mm)	Schmidt hammer test averages (mm)	Appearance after one year
SS-1	1:30	5.75	0	32	27	No rebound	Consolidation darkened the sand slightly and a small amount of blue-green deposit appeared on the surface
SS-2	1:30	4.60	0	33	32	No rebound	
SS-3	1:30	3.45	0	25	32	No rebound	
SS-4	1:30	2.30	0	18	33	No rebound	
SS-5	1:20	5.75	0	33	22	No rebound	
SS-6	1:20	4.60	0	37	17	No rebound	
SS-7	1:20	3.45	0	27	26	No rebound	
SS-8	1:20	2.30	0	18	25	No rebound	
SS-9	1:10	5.75	0	43	8	10	
SS-10	1:10	4.60	0	32	8	No rebound	
SS-11	1:10	3.45	0	25	19	No rebound	
SS-12	1:10	2.30	0	17	24	No rebound	
SS-13	1:30	5.75	10	37	27	No rebound	
SS-14	1:30	4.60	10	33	20	No rebound	
SS-15	1:30	3.45	10	23	35	No rebound	
SS-16	1:30	2.30	10	20	31	No rebound	
SS-17	1:20	5.75	10	32	15	No rebound	
SS-18	1:20	4.60	10	37	32	No rebound	
SS-19	1:20	3.45	10	28	25	No rebound	
SS-20	1:20	2.30	10	27	37	No rebound	
SS-21	1:10	5.75	10	42	8	9	
SS-22	1:10	4.60	10	38	10	10	
SS-23	1:10	3.45	10	28	15	No rebound	
SS-24	1:10	2.30	10	25	14	No rebound	
SS-25	1:30	5.75	20	37	19	No rebound	
SS-26	1:30	4.60	20	25	17	No rebound	
SS-27	1:30	3.45	20	27	27	No rebound	
SS-28	1:30	2.30	20	20	29	No rebound	
SS-29	1:20	5.75	20	40	15	No rebound	
SS-30	1:20	4.60	20	32	17	No rebound	
SS-31	1:20	3.45	20	25	24	No rebound	
SS-32	1:20	2.30	20	18	25	No rebound	
SS-33	1:10	5.75	20	37	11	9	
SS-34	1:10	4.60	20	42	10	No rebound	
SS-35	1:10	3.45	20	28	14	No rebound	
SS-36	1:10	2.30	20	20	20	No rebound	

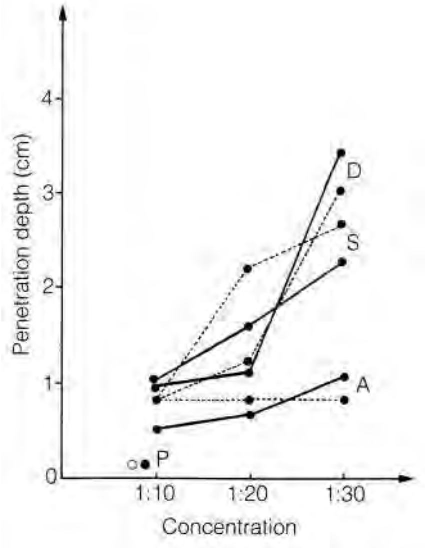


Figure 11
Puncture test: D = AC; A = AS (dry); S = SS; P = PS (prewetted).

Test Results and Discussion

Results show that the 1:10 AC, AS, and SS, and the 5–10% PS all exhibit good penetration capacity in both fine sand and the sand-gravel-clay mixtures. By comparison, the ability of these four types of consolidant to penetrate fine sand was greater than that of mixed sand. The loose sand requiring chemical consolidation in the Mogao grotto region is primarily the fine-grained windblown sand from the Mingsha mountain. However, since the installation of the wind fence, the fine-grained sand on the surface has been largely removed so that most of the sand remaining on the exposed surface consists of pebbles and coarse-grained sand. When the wind is not strong, sand is not readily blown from this type of surface. The sand deposits on the cliff slope and the conglomerate itself requires consolidation to combat erosion, which has accelerated since construction of the fence. All four of the consolidants exhibit ideal penetration for the purposes of these consolidation objectives, but each performs very differently.

Results show that sand samples consolidated with 10% PS had the highest water absorption rate. Within five minutes, the water absorption of the group A samples was 16.38% and that of the group B samples was 13.06%, with saturation being achieved in ten minutes. With AC, AS, and SS, samples had a slow absorption rate after the first five minutes. This was especially the case for the group A mixed sand samples. Water absorption for the group B samples was slightly higher. With AS it reached 5.86%; for group B samples after treatment with AS and SS for thirty minutes it was 10.26% and 9.65%, respectively. After soaking for forty-eight hours, the samples consolidated with AS and SS had the highest water absorption. Absorption in group B was even higher, that for the group A samples being 14.34% and 9.86%, respectively, and for the group B samples 22.09% and 22.43%, respectively. The reason for this could be that the intergranular films formed with AS and SS swelled after the consolidated sand had been soaked for a long period.

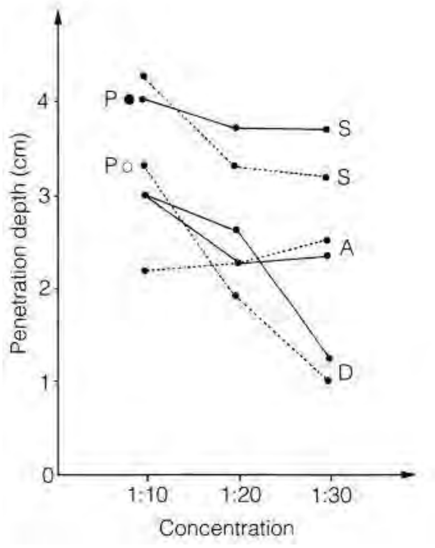


Figure 12
Penetration depth of the consolidants (at 5.75 l m^{-2}): D = AC; A = AS; S = SS; P = PS. Solid line: prewetted sand. Dashed line: dry sand.

PS is a binding material that exhibits good penetration on sand and rock, but, even more important, chemical bonding may occur among the silicate and the quartz and mineral components of sand and rock during the cementing process. PS does not appear to form a protective film on the surface and does not fill the pores of the rock; therefore, there is a high permeation rate and high water absorption. AC, AS, and SS are high-molecular organic polymers that readily form films and, when the concentration is high, tend to fill pores. Consequently, the water penetration rate is greatly decreased. As stated earlier, the permeability of the consolidated sand is a very important consideration at Mogao. In the past, wall paintings in caves were destroyed by rainwater that flowed into the caves. If the water permeation rate of the consolidated sand on the slope above the cliff were to decrease greatly after chemical consolidation, the runoff during heavy rains might enter the caves and further endanger the wall paintings. For this reason, in the event of large-scale interventions implemented in the future, a suitable drainage system should be installed on the top of the cliff face.

Water resistance tests of the consolidants showed that the 5% PS exhibited excellent water permeability and very strong water resistance. The water resistance of the AC, AS, and SS consolidated samples was lower.

Compressive strength tests indicated that the weathered conglomerate and consolidated sand treated with 10% PS had the highest values (12.37 and 8.70 MPa, respectively). Samples having the next highest strengths were the samples consolidated with AC and AS at a ratio of 1:10 (4.47, 1.65, 1.20, and 1.65 MPa, respectively). Those consolidated with SS were much lower, being 0.17 and 0.60 MPa—values only slightly higher than 0.11 MPa, the compressive strength of the unconsolidated material.

Wind-tunnel simulation tests of wind erosion of the consolidated rock samples indicate that the weak, semicemented argillaceous

conglomerate of the cliff was extremely susceptible to wind erosion. When the wind speed reaches 10 m s^{-1}, even a wind not carrying sand can bring about rock erosion. When the speed of a "clean" wind was greater than 15 m s^{-1}, there was a distinct erosion effect at a rate of 0.21 kg m^{-2} hr^{-1}. The wind-erosion effect of a sand-carrying wind was even greater. When the velocity of the sand-carrying wind reached 7 m s^{-1}, there was distinct erosion of the rock. When the velocity of the sand-carrying wind reached 10 m s^{-1}, there was a startling increase with an erosion rate as high as 123.80 kg m^{-2} hr^{-1}. When the velocity of the sand-carrying wind was 20 m s^{-1}, three-fourths of a $50 \times 50 \times 50$ mm rock sample was eroded within three minutes (Fig. 13). After the cliff rock had been consolidated with AC, AS, and SS, and with PS, it displayed a relatively ideal resistance to wind erosion. Comparatively, the samples exhibiting the best resistance were those consolidated with SS and PS. The erosion rates of these two were close to zero when the wind velocity reached 20 m s^{-1} even when loaded with sand. The high compressive strength and the high wind-erosion resistance of the PS consolidated samples are consistent. Conversely, the compressive strength of samples consolidated with a 1:10 water solution of SS was low, whereas their wind-erosion resistance was high. This appears to be because SS exhibits high flexibility after solidification.

Figure 13
Rock samples before and after the wind-tunnel test.

Freeze-thaw tests showed that samples consolidated with AC, AS, and SS, and with 10% PS, had good resistance; AS exhibited especially good resistance. Although the compressive strengths of the samples consolidated with AC, AS, and SS were comparatively low, their resistance to freezing and thawing was high. This is probably because these three organic polymers readily form films that coat the surfaces of rock grains and fill pores to some degree. Thus, they limit the uptake of moisture over a short period. Conversely, the rapid absorption by PS samples causes lowered resistance to freezing and thawing.

Because the climate of Mogao is that of an arid desert with an annual precipitation of only tens of millimeters, the water content of the rock is very low. Therefore, the resistance to freezing and thawing after consolidation is not a primary consideration in evaluating consolidants.

The on-site consolidation tests on the eastern side of the windbreak fence at the top of the cliff have shown that AC, AS, and SS, with PS, provided essentially similar permeation results. Best results of hardness tests of the surface of the consolidated sand were obtained with AS and 5% PS. An amount of spray of 5–6 l m^{-2} was best. When the amount of PS sprayed was less than 4 l m^{-2}, the surface hardness of the consolidated sand was significantly reduced. When the amount of AS sprayed was less than 4.60 l m^{-2}, the surface hardness of the consolidated sand was also significantly reduced. When the concentration of PS was less than 5% and when the concentration of AS was lower than 1:20 (equivalent to 5%), consolidation strength was clearly reduced. When sodium silicate was mixed with PS, there was no change in strength for six months. Over a longer period of time, the surface showed white efflorescence of salts and gradually softened, especially after rain or snow. Therefore, it is not appro-

priate to admix sodium silicate with PS for consolidation. The surface hardness of consolidated sand treated with AC and SS was low; when the concentration was below 1:10 (water), the consolidation hardness was even lower.

Results obtained by moistening the dry sand 1–2 cm prior to spraying the consolidants and then immediately spraying the consolidants increased the consolidating strength of the PS and AS.

In addition, from determinations of the surface hardness by a simple puncture test and using the Schmidt hammer, it can be seen that sand treated with AS and 5% PS has high hardness.

Conclusion

Laboratory and on-site tests of AC, AS, SS, and PS demonstrated that PS, AS, and AC are all comparatively good consolidants. However, under the conditions of the Mogao area, the organics did not perform overall as well as PS, which showed high weather and ultraviolet resistance. At the same time, the PS consolidated sand exhibited rapid water permeation. The area requiring consolidation at Mogao has been initially estimated to be about 70,000 m^2, including the top of the cliff and the weathered cliff face. Thus, some 300 t of consolidant will be required if the decision is made to undertake such a large-scale intervention. In any event, PS would be the material of choice. It is low cost (by comparison with organic resins), chemically and environmentally inert, and locally available, though the high molar ratio material preferred must be special ordered from the manufacturer.

Future objectives include continued improvement of the technology of chemical consolidation as well as consolidation of effective anchoring consolidated surfaces to prevent slipping in a seismic event. Much still needs to be done, and a small-scale test intervention is planned in an appropriate area. Only after evaluation of this test will further consideration be given to large-scale work.

Acknowledgments

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Notes

1 The high-molar potassium silicate used in this study was provided by the Lanzhou Oil Refinery, and all the organic consolidants and monitoring instruments were provided by the Getty Conservation Institute.

2 The authors were unable to cut the conglomerate into regular samples by machine because the cementation was loose. All that could be done was to prepare samples of close to 50 × 50 × 50 mm by hand shaping.

3 The adhesive was calculated after dilution.

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Research into the Control of Damage by Windblown Sand at the Mogao Grottoes

Ling Yuquan, Qu Jianjun, Fan Jinshi, and Li Yunhe

Windblown sand has long posed a severe problem at the Mogao grottoes. Carried by prevailing seasonal winds from the extensive dunes on the plateau above the grottoes, the sand erodes the cliff slopes and accumulates at the base of the grottoes. Some 2,000 m^3 of sand are swept up and removed annually. Moreover, sand and accompanying dust infiltrate the grottoes themselves, where they obscure the ancient sculptures and wall paintings.

Previously, experimental windbreaks of brush and reed have failed to control this problem. In 1989, the Lanzhou Desert Research Institute of the Chinese Academy of Sciences, the Dunhuang Academy, and the Getty Conservation Institute initiated a study of the problem to develop preventive measures. The Desert Research Institute designed a 3.7 km wind fence, in an A-shaped configuration. The design was based on seasonal and diurnal wind velocity and direction data gathered from the Getty Conservation Institute's solar-powered meteorological station on the cliff top and from sand traps used to determine quantity and particle size. The stability of the dunes with respect to growth and movement was also investigated. Data indicated that seasonal wind changes would disperse the accumulation of sand at the fence. For construction of the fence, the Getty Conservation Institute provided an ultraviolet-stabilized, knitted aerotextile, which reduced wind velocity by approximately 50%, and the Dunhuang Academy erected the fence in 1990. Although some reconfiguration of the fence has been necessary where heavy sand accumulation has not been subsequently dispersed, the fence has reduced sand at the cliff base by about 62%. In time, this efficiency is expected to increase, as the present accumulation is believed to derive from residual sand between the fence and the cliff edge. The fence is expected to have a life of at least fifteen years, by which time the vegetation windbreak now being planted, with a drip irrigation system, should be well established.

Background

The Mogao grottoes are a national protected site of the first rank and are also a world famous treasure-house of ancient Chinese art. It has been

called the "art gallery of the world" and "a museum on walls." The murals and polychrome statues inside this immense group of caves, and especially the information content of the murals, embrace a broad range of complicated themes. They occupy an extremely important position in Chinese and world art history.

It has been sixteen hundred years since the initial excavations were made at Mogao. During this period, the effects of natural and human factors have caused damage of differing degrees to the caves, murals, and statues. Windblown sand is one of the most damaging factors. Erosion or denudation by windblown sand has left many of the caves with thin roofs and poses a direct threat to the conditions of preservation and to the environment of the murals. Accumulation of sand has resulted in pressure on the roofs. Sand accumulation on the walkways blocks traffic. Sand and dust have also abraded the murals.

In the early 1960s, a plan to control sand was formulated and small-scale sand-control experiments were initiated. However, there was insufficient recognition of the severity of the damage brought about by windblown sand, and not enough serious consideration was given to the importance of controlling windblown sand. Furthermore, because the methods taken for controlling sand were inappropriate, and because of lack of funding, the sand control experiments could not be continued. For example, the local dry brush fence built on the edge of the cliff top led to accumulation of sand on top of the cliff, creating a new source of sand near the cliff face and a latent danger. Another instance was the digging of sand-control ditches on the top of the cliff. The ditches were quickly filled by sand carried by the westerly wind. The principal reasons for these failures were that there was insufficient understanding of the patterns of wind and sand movement and poor awareness of the severity of the damage that they bring about. Therefore, for many years a passive approach was taken, and sand that had accumulated in front of the caves was removed by hand. After the World Heritage Committee of Unesco listed the Mogao grottoes as a World Heritage Site in 1987, research on damage to the Mogao grottoes by windblown sand was given serious consideration and support by leaders in various departments and at various levels. In July 1989, the Dunhuang Academy and the Lanzhou Desert Research Institute of the Chinese Academy of Sciences with the Getty Conservation Institute initiated experimental research on sand control using knitted polyethylene textile as the windbreak fence material.

The research was carried out in two stages. The first stage, from October 1989 to September 1990, involved making a topographic map (scale 1:1,000) of a 2 km^2 test area, then monitoring and studying the patterns of wind and sand movement using meteorological data and information collected from sand traps. The second stage began in October 1990 with the construction of the windbreak fence and continued until the end of 1992. The main objectives during this stage were to monitor the effectiveness of the fence on the basis of patterns of windblown sand activity and calculations of the intensity of the activity.

Natural Setting

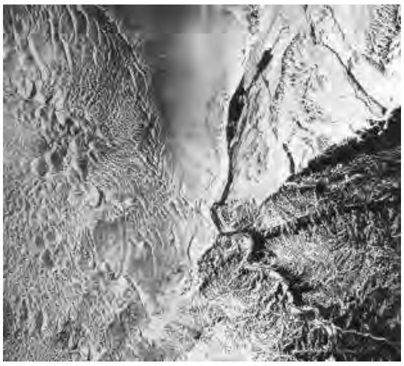

Figure 1
Satellite image of the Mogao grottoes area.

Location

The Mogao grottoes are located on the southeastern margin of the Dunhuang oasis 25 km from the city of Dunhuang. The Sanwei mountains are to the east, the Mingsha sand dunes to the west, with the Daquan River valley between and the vast Gobi Desert to the north (Fig. 1).

The caves were excavated in the cliff on the west bank of the Daquan River (Fig. 2). The stratum in which the caves were excavated is the alluvial and pluvial Jiuquan conglomerate in which there is argillaceous and calcareous cementation. This is a recent geological formation, and the rock is poorly cemented. Thus, it weathers and is eroded rapidly by the wind.

This region is at the western end of the Hexi corridor in the hinterland of northwestern China and is constantly under the influence of the Mongolian high pressure system. The climate is characterized by extreme aridity, low precipitation, great seasonal temperature variation, and frequent windblown sand activity. The average annual atmospheric temperature at Mogao is 10.3 °C. The highest temperature ever recorded at the grottoes was 40.6 °C on 27 July 1965 and the lowest absolute temperature was −21.5 °C on 23 December 1965. The average annual precipitation level is 23.2 mm and annual evaporation is 3,479 mm, 150 times the precipitation level; and the average relative humidity is 32%.

Wind conditions

The Mogao grottoes are situated in a windy region having an annual average wind velocity of 3.5 m s^{-1}. However, it is a region in which there is great variation in wind direction (Fig. 3). The south wind is the most common and accounts for 31% of the wind frequency. The southerly winds, including the south-southeast and south-southwest winds, account for 47.9% of the wind frequency. However, the wind speeds are not very great. For example, 39% of the south winds have a wind speed less than that required for saltation of sand (5.0 m s^{-1} at a height of 2 m), whereas only 1.5% of the winds have a velocity higher than 8.0 m s^{-1}, and 59.2%

Figure 2
Overall view of the Mogao grottoes.

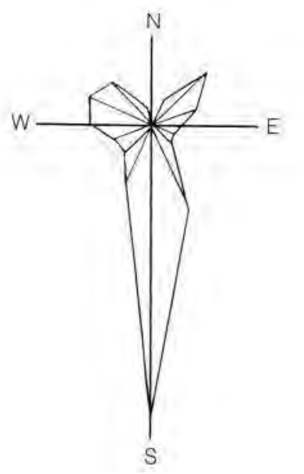

Figure 3
Wind rose at the Mogao grottoes (1990–91).

have a velocity greater than 5.0 m s^{-1} and less than 8.0 m s^{-1}. Wind-tunnel experiments in Lanzhou have demonstrated that winds with velocities in this range have a very limited sand transport capacity. They can barely move the sand on the surface of the dunes to form ripples. They have even less effect on the sand and gravel of the Gobi Desert. The next prevailing wind is the westerly wind. The frequency of the westerly winds (southwest, west-southwest, west, west-northwest, and northwest) is 28.1%. However, they account for 31.9% of the sand-transport capacity. Most (70.8%) of the westerly winds are less than the saltation speed, and 23.4% have wind speeds greater than 5.0 m s^{-1} and less than 8.0 m s^{-1}, accounting for 28.9% of sand-transport capacity. The frequency of wind speeds greater than 8.0 m s^{-1} amounts to 5.8% on average and accounts for 71.1% of the sand-transport capacity. In other words, the common southerly winds are weaker, and the westerly winds are stronger. Thus, the westerly winds are the principal cause of sand accumulation and damage in front of the grottoes. The frequency of the easterly winds is only 14.8%, and they account for 27.5% of the sand-transport capacity. The major damage caused by the easterly winds is erosion and denudation of the cliff face. It also has an effect, that cannot be undervalued, of inhibiting the eastward drift of sand at the top of the cliff.

The formation and characteristics of this type of average flow field is affected by the large-scale topography—such as the dynamic and thermal action of the Qinghai-Xizang plateau (Luo 1982) and the Qilian and Tian mountains—as well as small-scale landforms, the Sanwei and Mingsha mountains, and the desert and surface of the Gobi (Ling 1988). Specifically speaking, the strong west winds are dominated primarily by the circulation of the prevailing westerly wind and large-scale weather patterns. The weak, frequent southerly winds derive from local currents or from the Qilian mountains. There were some obvious patterns in the seasonal and daily variations of the southerly winds, which are more common in evenings and in the winter months (from October to February). Although the winds are weak, they display considerable directional stability.

This typical circulation pattern shaped the unique landform of the Mingsha mountain and led to the formation of a group of relatively stable but complex sand dunes. There were clear seasonal variations, with coarse sands covering the upper-middle section of the slope in the dominant wind direction.

On the basis of site inspection and research, it was discovered that the sand in this region is primarily derived locally—that is, under the action of winds of different frequencies, of different strengths, and of multiple directions, local sands were transported back and forth in the area.

Patterns of Sand Movement in the Mogao Grottoes Region

Characteristics of sand movement

From an overall standpoint, sand movement in this region belongs to the category of sand flow from the Gobi Desert. Specifically, intense saltation of sand grains raises the height of sand transport and makes the amounts

Figure 4
Patterns of sand accumulation in different directions around a plant.

of sand carried in the upper and lower layers relatively uniform. Under such conditions, sand is transported and tends not to accumulate. However, winds from different directions, of different frequencies and different intensities, alter the characteristics of the sand movement, making it more complex. For example, there can be sands of different granularity accumulated in different shapes in different directions around a plant (Fig. 4). Accumulation of sand can only undergo changes in shape but cannot continuously increase in volume. Sand ripples and dunes are no exception to this. There are also severe limitations imposed by multiple changes of wind direction. In Figure 4, the formation of coarse sand ripples at the leeward side under the action of the strong west wind can clearly be seen. The sand was from a sand and gravel surface. Not only is the area of accumulation large but the height and width of the ripples are also large. Sand formed by southerly winds is very fine-grained and displays a small area of accumulation, and the height and width of the ripples are small. This sand originates from drifting sand dunes. The east wind has a reverse transport capacity in respect to sand accumulated at the tops and sides of the cliffs and can form accumulations of sand behind vegetation. The scale and granularity of the sand deposits are smaller than those deposited by the west wind but larger than those deposited by the south wind. There are clear seasonal variations in the shape of sand accumulation, and the changes are completely congruent with the pattern of changes in average flow fields.

Pattern and intensity of windblown sand activity

To further understand the patterns of movement of the wind-driven sand, we selected three profiles for monitoring the distribution, movement, and deposition of sand on the top of the cliff and at the cliff base and conducted more than two years of monitoring and research. The directions of the monitored profiles are the same as the wind directions.

The amount and rate of sand transport was monitored at a height of 0–20 cm, and the average wind velocity was monitored at heights of 0.2 and 1.5 m above the ground surface. Five observation points were established for each profile, and comparative monitoring was performed simultaneously.

At the same time, five sand traps were set up in front of the grottoes (Caves 152, 256, 404, 208, and 154) at different locations to measure the daily sand accumulation from 1800 to 0800 hours. These times were established to avoid disturbance by visitors during the day.

A small sand dune was also selected, and studies were made of change in its shape and rate of movement, with contour lines mapped each time after a gusty wind. Determinations were also made of shifts in the ridge using marker sticks.

Monitoring results

Characteristics of windblown sand distribution from the sand drift to the top of the cliff during west or northwest winds can be seen in Tables 1–3.

Note that the sand-transport rate increased rapidly with increasing average wind velocity. The relationship between the transport rate (q) and the threshold deflation velocity (V_t) is as follows (Ling 1992):

$$q = 8.95 \times 10^{-1} (V - V_t)^{1.9}$$

where V_t is the sand grain deflation velocity. V_t is 5.0 m s^{-1} (at a height of 2 m) for sand grains of 0.125–0.250 mm in size. The roughness of the ground surface in the Gobi Desert is 0.115 cm, which is much higher than that of drifting sand (average roughness at the surface of the shifting sand being 0.005 cm). Therefore, the threshold grain-deflation velocity in the Gobi Desert is undoubtedly high. Theoretically, grain-deflation velocity is proportional to the square root of the diameter of the sand grain, that is, $V_t \propto d^{1/2}$. For the same wind velocity, the sand-transport rate is lower in the Gobi Desert than that in an area of shifting sand. However, as a result of long-term transport by southerly winds, the ground surface of the Gobi Desert is covered with numerous small sand dunes, and the threshold deflation velocity is thus close to that of drifting sand. To calculate the maximum possible rate of sand transport, the authors used 5.0 m s^{-1} as the average threshold deflation velocity. As shown in Table 1, when the average wind velocity was about 6.0 m s^{-1}, the sand-transport rate was about the same at all five observation points along the profile. When the average wind velocity increased to 8.0–9.0 m s^{-1}, there was a marked change in the sand transport rate and a high rate (relative to the sand and gravel of the Gobi Desert) was observed at observation point no. 3. This was because of the sandy character of the drifting sand transported by the westerly wind. After carrying sand for 500–700 m, the westerly winds deposited part of their load in the depression around observation point no. 3. Following this, some of this sand was carried to a sand and gravel plateau about 5 m lower than the previous ground surface. It was then carried another 200 m to the top of the cliff or near the cliff face. The abrupt change in the landforms led to separation of the flow into layers and deposition of sand in separate regions.

Table 1 Characteristics of windblown sand with a west or northwest wind

Item and location	No. 1 Drift sand	No. 2 Gobi	No. 3 Gobi	No. 4 Gobi	No. 5 Cliff top
$V_{1.5}$ (m s^{-1})	6.1	5.8	6.3	6.5	6.4
q (g cm^{-1} min^{-1})	0.501	0.344	0.386	0.305	0.366
$V_{1.5}$ (m s^{-1})	9.4	8.2	8.2	8.9	8.8
q (g cm^{-1} min^{-1})	4.429	3.960	4.228	3.161	3.459
$V_{1.5}$ (m s^{-1})	10.4	8.9		10.3	10.7
q (g cm^{-1} min^{-1})	9.307	5.864		6.199	7.960
$V_{1.5}$ (m s^{-1})	12.6	11.2	12.1	15.6	14.3
q (g cm^{-1} min^{-1})	16.750	10.300	10.825		

All five locations are on the plateau above the grottoes, at various points between the edge of the cliff and the Mingsha dunes. "Drift sand" and "Gobi" refer to the characteristics of the surface, the latter being gravel.

Table 2 Characteristics of windblown sand with a southwest wind

Item and location	No. 1 Drift sand	No. 2 Gobi	No. 3 Gobi	No. 4 Gobi	No. 5 Cliff top
$V_{1.5}$ (m s^{-1})	5.8	5.4	5.5	6.0	6.1
q (g cm-1 min^{-1})	0.473	0.136	0.093	0.039	0.095
$V_{1.5}$ (m s^{-1})	8.5	7.2	7.5	7.8	7.8
q (g cm^{-1} min^{-1})	1.960	1.586	1.132	0.717	0.509

See note to Table 1.

Table 3 Characteristics of windblown sand with an easterly wind

Item and location	No. 1 Drift sand	No. 2 Gobi	No. 3 Gobi	No. 4 Gobi	No. 5 Cliff top
$V_{1.5}$ (m s^{-1})	6.7	6.2	6.3	6.6	6.8
q (g cm^{-1} min^{-1})	0.824	0.613	0.565	0.573	1.480
$V_{1.5}$ (m s^{-1})	8.3	7.7	7.8	8.0	8.8
q (g cm^{-1} min^{-1})	5.312	3.143	3.614	4.601	6.798

See note to Table 1.

Sand accumulation at the base of the cliff occurs only when the slope angle is larger than the angle of repose or after a gusty wind when sand may slide down the cliff face, with great variations occurring in the granularity of the accumulated sand. Generally, there can be two peaks of annual change in sand accumulation in front of the caves. The principal peak appears in April to June, during which period the east and west winds are dominant. The next peak appears from August to October. On the basis of the observations of the distribution of sand-transport rates from the profiles, most of the sand transported at each section was the result of local deflation. Only when the wind velocity was greater than 11.0 m s^{-1} did long-distance transport of sand occur (Table 1.)

The amount of sand transport varies with height above ground and is closely related to the positioning of the sand-control installation and the height of transport of the wind-driven sand. Under ordinary conditions, the height of transport of drifting, windblown sand above the surface of the shifting sand is less than 1 m, and more than 95% of the sand is transported in a zone less than 20 cm above the ground surface. Of this, 80–90% of the sand is carried in a zone 0–10 cm above the ground surface. That is to say, drifting sand can be stabilized either by reducing wind velocity or by controlling the movement of the windblown sand. If, at the same time, we can take measures to intercept the sand on the windward side, then a protection system can be established in which an emphasis on stabilization is combined with blockage.

Wind speed is usually high on the Gobi Desert because of the open topography. At the same time, the gravel nature of the ground surface increases the rebound action of the saltating sand grains. Thus, sand

can be transported in wind higher than 1 m above the ground; but only 3–4% of the sand is transported in this way. On average, less than 80% of sand is transported in the layer 0–20 cm above the ground. There is a lack of sand sources in the Gobi, and the windblown sand flow is in a very unsaturated state. Under such conditions, protective measures suited to the circumstances are ordinarily adopted in regions in which there is a danger of damage by windblown sand.

In the sand and gravel regions of the Gobi Desert, there is a fixed source of sand, the gravel is fine, and there is not a very strong rebound action on the part of the saltation sand grains. A higher concentration of sand is carried by the air in the gravel region of the Gobi. For this reason, the characteristics of sand movement in the sandy regions of the Gobi are a combination of those in the gravel region and those at the surface of drifting sand. The results of the determinations indicate that the sand-transport rate in the 0–20 cm layer exceeds 93.32%, which is very close to that on the surface of the drifting sand, when the average wind velocity is 10.4 m s^{-1} at 1.5 m above the ground surface. However, there is a sand-transport volume of only about 1% in the layer 1 m above the ground surface and a volume of only 0.19% in the layer 210–230 cm above the ground surface. The distribution of sand in the 0–2 cm layer is relatively uniform. The windblown sand flow belongs to the category of low concentration, unsaturated sand-transport intensity.

Southwesterly windblown sand flow

It can be seen from Table 2 that the amount of sand transported from the Mingsha mountain to the top of the cliff by the southwesterly winds is much less than that carried by the northwest wind. Although there is an ample supply of sand, the average flow field limited and slowed the transportation capacity of the southerly and southwesterly winds. In addition, the Mingsha mountain itself acts as a barrier to the southwest wind. For this reason, the sand-transport rate is gradually reduced from the Mingsha mountain to the top of the cliff.

Easterly windblown sand flow

As can be seen from Table 3, there is a clear increase in windblown sand flow intensity under the actions of easterly winds. That is to say, easterly winds have a definite reverse-direction transport capacity on sand that has accumulated over long periods on the cliff top and cliff face. The findings in Table 3 reflect a back-and-forth transport of sand in this region, which creates great difficulties for sand-control installations.

Sand-Control Measures and Implementation

Design principles

The objective is to protect the Mogao grottoes from damage by windblown sand or to lessen the degree of damage. Specifically speaking, this means controlling the large quantity of sand carried by the westerly winds

from accumulating on top of this cliff, near the cliff face, and on the walkways below, and controlling wind erosion and abrasion of the bedrock caused by the easterly winds. At the same time, the action of the southerly winds, which are of the highest frequency, needs to be taken into consideration. Therefore, design of sand-control programs must be comprehensive and economical and be able to deal with multiple wind directions.

Design basis

The observation and research carried out in the earlier phase not only deepened an understanding of the patterns of sand drift in this region but also provided valuable scientific bases for the design of sand-control programs.

Basic theoretical calculations show that maximum sand-transport capacity of westerly winds in this area is 13 m^3 m^{-1} yr^{-1}. In other words, every year 12,000 m^3 of sand can accumulate along the 900 m long cave area, with a considerable portion of the sand accumulating on the cliff face and some accumulating on the walkways in front of the caves. Nearly the same amount of sand is transported in the reverse direction by the easterly winds. On this 900 m long cliff, 11,500 m^3 of sand can be transported from the top of the cliff toward the Mingsha dunes and be distributed over the approximately 2 km^2 sand-and-gravel portion of the plateau. The difference between the maximum amount of sand that can be transported from east to west and the maximum amount of sand that can be transported from west to east is approximately 520 m^3.

It is important to note that the maximum possible sand-transport capacity of the southerly wind is 11,000 m^3 m^{-1} yr^{-1}. The southerly winds provide new sources of sand for transport by the easterly and westerly winds but do not cause direct damage to the caves.

In the present phase, a synthetic knitted textile windbreak fence is the principal method being used to control sand from accumulating in front of the caves. Testing is also taking place on chemical consolidation to prevent weathering of the cliff rock.

Windbreak fences are frequently used to block sand flow in a single direction. In this case, sand-blocking efficiency is generally 80–90%. If the intensity of the windblown sand is high, the windbreak fence will be buried in a few years and a new fence will need to be installed on the top of the old fence.

In view of the aforementioned circumstances, and in consideration of the characteristics of the windblown sand activity in this region, an A-shaped windbreak fence system was designed and installed in a triangular form (Fig. 5). The three sides of the triangle are at an effectively larger angle to the dominant wind directions and at a smaller angle or nearly parallel to the secondary wind directions. Thus, the fence can block sand carried in the dominant wind directions and divert the sand carried in the secondary wind directions. It is an effective and comprehensive control system that is capable of controlling windblown sand from multiple wind directions. The fact that ripples that are formed on the surface of the

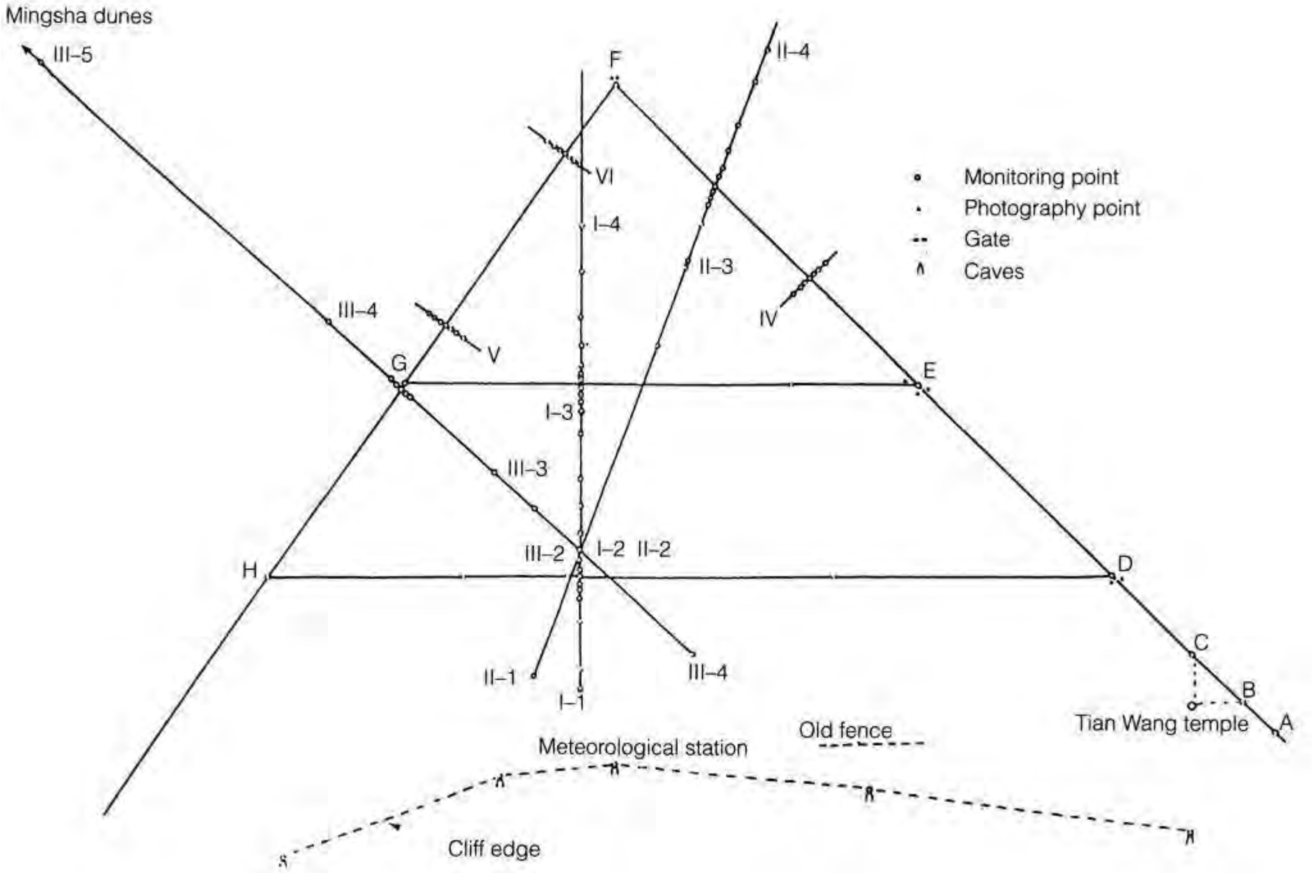

Figure 5
Plan of the synthetic textile wind fence on the plateau above the grottoes, and sand-monitoring Sections I–VI.

accumulating sand on the windward side are perpendicular to the fence provides the most convincing proof of its sand-diverting capacity.

Effectiveness of Sand Control

The windbreak fence is 1.8 m high with a void space of 20% and a resistance coefficient of 1.5. When the average wind velocity is 11.1 m s^{-1}, the windbreak fence is subject to a wind pressure of 17 kg m^{-2}. Angle steel posts were used for the fence, set with 3 m spacing. The posts were installed in a 20 × 20 × 30 cm concrete foundation. The textile net was further reinforced with 45° wires running diagonally between posts.

To guard against sand accumulation in front of the caves, installation of the windbreak fence was completed by the end of November 1990. The amount of sand that accumulated in front of the caves during March 1991 was 75% less than that during March 1990. The sand accumulated in front of the caves cannot reflect the true effectiveness of the windbreak fence for now. The reason for this is that the gusty easterly winds cause sand accumulated on the surface of the cliff to slip down to the front of the caves. However, the following two observations show the effectiveness of the windbreak fence. First, the amount of sand in the sand traps in front of the caves was clearly decreased, the grain size became coarser, and there was a marked increase in gravel content. Second, there was decrease or disappearance of yellowish layered sand on the top of the cliff and on the surface of the cliff face.

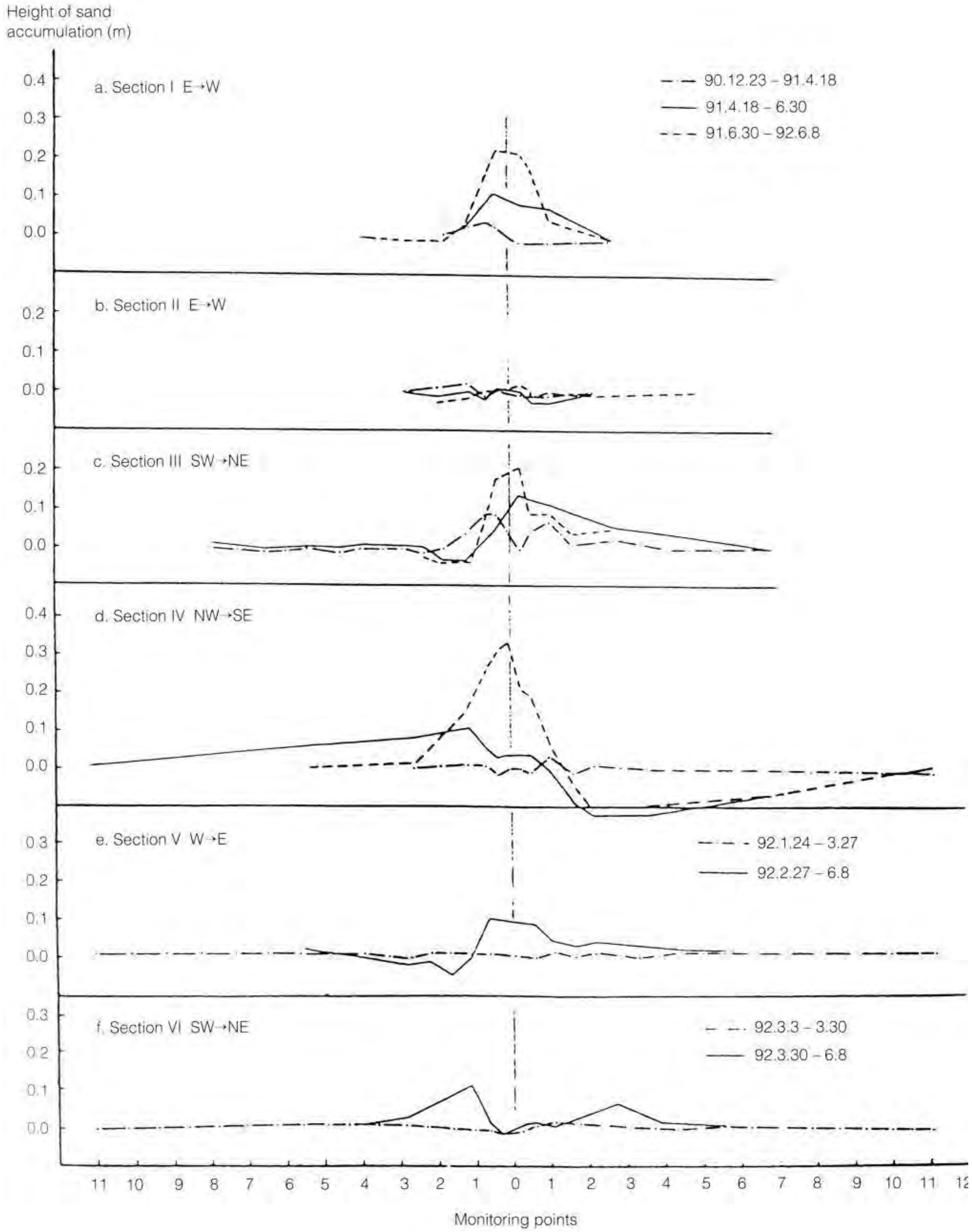

Figure 6
Sand accumulation profiles at monitoring points along Sections I–VI.

To deter sand accumulation in front of and in back of the fence, other measures were taken. In order to monitor the effectiveness of the windbreak fence, six sections were selected along the fence for study of the sand accumulation (Fig. 5). The results are shown in Figure 6. Section I

is one of sand accumulation close to the top of the cliff and parallel to the cliff face. Small quantities of sand were transported from both the east and west, which caused accumulations of sand both in front of and in back of the fence. Some of this was underground sand that had been scooped out during the installation of the fence and was later deposited around the fence. Section II was situated to the west of Section I and was close to the center of the windbreak fence system. Here there was no clear sand accumulation or erosion. Section III monitored a section of the fence aimed at preventing accumulation of sand by the southerly winds. There was severe sand accumulation in front of the fence, and there was erosion in back of the fence. Section IV was a section of the fence installed to prevent accumulation of sand by the westerly winds. In front of the fence, there was an accumulation of sand (due to the action of the northwesterly wind), and there was also erosion (due to the sand deflation action of the northeast or westerly winds). There was also clear accumulation of sand in back of the fence. From this it can be seen that the amounts of sand that accumulated inside and outside the windbreak protection system were very slightly less than the amounts that were calculated theoretically. Large amounts of

Table 4 Characteristics of windblown sand at cross Section I with a northeast wind (see also Fig. 5)

Item and location	20 m in front of no. 1	1 m in front of no. 2	1 m to the rear of no. 3	20 m to the rear of no. 3
$V_{1.5}$ (m s^{-1})	8.4	8.3	4.7	6.5
q (g cm^{-1} min^{-1})	0.644	2.141	1.442	0.072

Table 5 Characteristics of windblown sand at cross Section III with a southwest wind (see also Fig. 5)

Item and location	50 m in front of no. 1	20 m in front of no. 2	1 m in front of no. 3	1 m to the rear of no. 4	20 m to the rear of no. 5
$V_{1.5}$ (m s^{-1})	6.2	5.7	4.6	2.8	4.2
q (g cm^{-1} min^{-1})	0.356	0.284	0.165	0.061	0.002

Table 6 Characteristics of windblown sand at cross Section IV with a northwest wind (see also Fig. 5)

Item and location	10 m in front of no. 1	1 m in front of no. 2	1 m to the rear of no. 3	10 m to the rear of no. 4
$V_{1.5}$ (m s^{-1})	7.7	6.7	4.0	3.9
q (g cm^{-1} min^{-1})	0.146	0.074	0.187	0.004

sand had been diverted. This clearly indicates the great effectiveness of the windbreak fence.

Characteristics of dynamic transport of sand

Comparisons of sand accumulated at different locations along the fence demonstrated the effectiveness of the windbreak fence. Examples are shown in Tables 4–6. As indicated in Table 4, when there were northeasterly winds in Section I, comparatively small amounts of sand transport took place 1 m in front of and in back of the fence and 20 m in back of and in front of the fence, due to insufficient sand sources, even though there was a strong wind force. The small quantity of sand transport at 20 m in back of the fence was also a result of the sand-blocking effectiveness of the fence. This is congruent with the state of sand accumulation described above. The effectiveness of this type of sand control is clearly reflected in Sections III and IV. At distances of 10 and 20 m in back of the fence, the quantity of sand transport was only 0.7–2.7% of the quantity of sand transport at the corresponding distances in front of the fence. It can be said that less than 5% of the windblown sand will be able to reach the top of the cliff after it has passed through the protection system. At present, most of the sand that has gathered in front of the caves is the product of many years of accumulation. There were very great differences in the quantity and composition of the accumulated sand, particularly under the influence of easterly winds.

In summary, comprehensive measures against damage by windblown sand are necessary, especially in the Mogao grottoes region. The diversity and complexity of windblown sand activity makes comprehensive control even more necessary. A comprehensive, overall sand-control program is dependent on a thorough understanding of the patterns of windblown sand movement.

Conclusion

Different frequencies and intensities of winds from multiple directions characterize the average flow field in the Mogao region. Serious sand accumulation and severe wind erosion are two major forms of windblown sand damage to the Mogao grottoes brought about by this type of flow field.

On the basis of test data on patterns of windblown sand activity in this region, the triangular windbreak fence was capable both of blocking the drifting sand carried in the dominant winds and of diverting fixed quantities of accumulated sand in the secondary wind directions. This multifunctional fence system has effectively controlled windblown sand (decreasing it by about 95%) and has prevented accumulation of sand in front of the caves (reducing it by about 75%).

Damage by windblown sand must be controlled in a comprehensive way. After preliminary control of sand erosion in front of the Mogao grottoes was achieved, the problem of wind erosion of the cliff face became even more pronounced. For this reason, it is also necessary to carry out effective chemical consolidation of the cliff face without delay. In

addition, further research on developing vegetation windbreak fences is a task of significance.

Maintenance—by removal of accumulated sand, as necessary—and monitoring of the windbreak fence are the keys to increasing the effective life of the fence.

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Desert-Adapted Plants for Control of Windblown Sand

Po-Ming Lin, Neville Agnew, Li Yunhe, and Wang Wanfu

In the northwest of China, as in other desert regions of the world, erosion of historic and cultural sites by windblown sand is a serious problem. Sites that were long abandoned are often buried by sand and thus preserved; as, for example, the remarkable preservation of archaeological and organic remains discovered in the Takla Makan desert of Xinjiang. However, at sites open to the public, such as Mogao, the accumulation of sand needs constant removal and diverts resources and staff needed for other functions. Here sand and dust settle on the art within the grottoes, and the attrition of windblown sand has thinned the rock of the upper-level caves. Sand control is thus a matter of priority.

The problem of windblown sand is, in general, more than one of preservation of cultural heritage resources. Migrating dunes block roads and rail lines, and the Desert Research Institute (IDRAS) in Lanzhou (an institute of the Academia Sinica) has developed expertise in dealing with these problems in this area of China, and in understanding the larger issues of desertification. Elsewhere in these proceedings the results of the windfence designed by IDRAS are reported (Ling et al. herein). The present paper complements that of Ling et al.

Previously, attempts at sand control by dry-brush fences were undertaken at Mogao. These were ineffectual. In 1990, the synthetic fabric windbreak fence, referred to above, 3.4 km long, was built on the plateau above the grottoes as a measure to control the problem. This fence has reduced sand accumulating at the base of the cliff by 60%. The fence was designed using data on wind speed, wind direction, and wind duration collected by an automatic weather station on the cliff top. The design takes into account diurnal and seasonal changes in wind and minimizes accumulation of sand along the fence. The fencing material has a life expectancy of at least fifteen years. As a permanent solution to sand control at Mogao, a vegetation windbreak was planted. Because of the extreme aridity of the region, it was necessary to select plant species adapted to the harsh environment. The following reports the results of the trial windbreak and its extension.

A trial vegetation windbreak fence was planted at Mogao in May 1992. An experimental area 200 m long and 10 m wide was selected to supplement the performance of the fabric fence. A drip irrigation system with twelve hundred emitters was installed. Four species of indigenous desert-adapted plants, totaling about six hundred young trees, were planted. These plants can tolerate extreme weather conditions and saline sand. After one year, the results looked promising. The survival of the four species ranged from 82% to 100%. Among them, *Haloxylon ammodendron* had the highest survival and grew fastest. The experimental site was expanded to 8,000 m^2 in the spring of 1993.

The Mogao grottoes, one of China's most prestigious sites, has been affected by sand erosion since the earliest times. Excavated into the cliff face on the west bank of the Daquan River, the grottoes consist of some five hundred caves divided into southern and northern regions. In the southern region, the caves are decorated with wall paintings and sculptures; most of the caves in the north region are not decorated. At the top of the cliff is a plateau. Part of the Gobi Desert, the plateau is covered with sand, pebbles, and a small amount of vegetation. The plateau ends about 1 km to the west of the cliff, where the huge Mingsha sand dunes rise abruptly. These are stable, yet feed sand migration to the grottoes, and are themselves replenished by sand farther to the west.

The persistent wind is from the south with low speed. Minor wind directions are from the west and east but with much higher speed than that of the south wind. The average wind speed is 3.5 m s^{-1}. The highest wind speed can reach 16 m s^{-1}. Prevailing winds drive sand toward the cliff where an approximately 35–45° slope has been eroded between the plateau and the vertical face of the escarpment.

There is no record of how the sand problem at the Mogao grottoes was dealt with in ancient times. In the 1950s and 1960s, site personnel tried to stop sand migration by erecting dry-brush fences at the edge of the cliff and at the foot of the Mingsha dunes. None of these methods was effective. As described by Ling et al. (herein; Ling et al. 1993), a synthetic fabric windbreak fence was designed and constructed as part of the collaboration with the Getty Conservation Institute. Prior to the installation of the synthetic fabric fence, about 3,000 m^3 of sand were swept up and removed annually from the grotto site. Frequently, walkways and entrances to caves were blocked by accumulated sand; it gets into caves via entrances, and fine dust is deposited on the surfaces of sculptures and wall paintings, obscuring them. In addition, sand erosion of the cliff slope has cut through the rock roofs of the upper-level caves, resulting in collapse in some instances.

An A-shaped synthetic fabric windbreak fence 3.4 km long was built on the plateau above the grottoes in 1991 to control the sand problem. The fence reduced sand accumulation at the base of the cliff by 62% (Ling et al. 1993). However, the fence may be subject to vandalism as well as eventual deterioration, and sand accumulation has occurred in some areas of the fence, necessitating manual removal. As a permanent solution

to the problem, a vegetation windbreak was proposed—one that would supplement the fabric fence and eventually supplant it.

The objective was to establish a permanent zone of indigenous, desert-adapted plants on the plateau to control sand movement.

A drip irrigation system was installed to provide adequate water during the period when the plants were establishing themselves. Other factors that needed to be taken into consideration were climate, choice of appropriate plants, water quantity and quality, and soil type.

Location

The test site is located about 1 km south of the existing synthetic fabric fence and about 100 m from the nearest sand dune (Fig. 1). To protect the young plants while they were establishing themselves, a supplementary synthetic fabric windbreak fence was built. This fence is 1 m tall, 200 m long, and was situated between the experimental area and the sand dunes, parallel to the tree lines.

Soil

The area between the grottoes and the Mingsha dunes is typical Gobi Desert, consisting of sand, pebbles, some silt, soluble salts, and no organic matter. This type of soil has very high permeability and low moisture-retaining capability. Furthermore, evaporation is much higher than precipitation in this region. Thus, topsoil was brought in and placed in the holes for the seedlings.

Vegetation

Haloxylon ammodendron, Tamarix chinensis, Calligonum arborescens, and *Hedysarum scoparium* were selected for the experiment. These plants are native to the region; tolerate dry, cold, and hot weather; and survive in saline soils. They grow 6–9 m high if enough water is provided; and they mature, bloom, and seed within four to five years. Seedlings were obtained by the Dunhuang Academy from a nursery in Lanzhou.

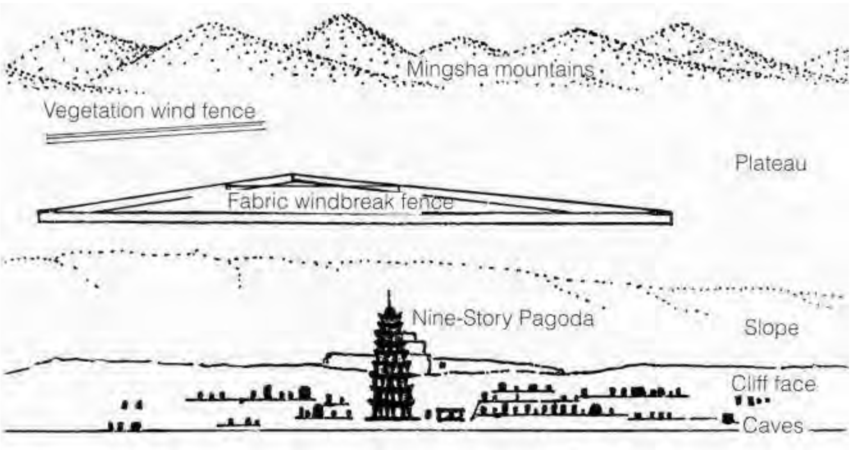

Figure 1
Schematic drawing showing the location of the vegetation windbreak fence.

Water

Annual precipitation in the Dunhuang area is 16–24 mm. Water for irrigation and daily living at the Mogao grottoes is obtained from the Daquan River, which flows through the site. The ultimate source is mostly meltwater from snow in the distant Qilian mountains. The river contains a high concentration of salts. It has long been used to periodically irrigate the trees growing in front of the grottoes, without harmful effects to them.

Drip Irrigation

Drip irrigation systems are more effective and less wasteful of water than traditional surface furrows. A network of closed conduits supplies small amounts of filtered water to the plants according to a regular schedule. Weed growth and water consumption by weeds are limited, because only a small surface area of the soil is irrigated.

The major disadvantage of drip irrigation systems is clogging of emitters and drip lines. Clogging can be physical, chemical, or biological. Physical clogging is caused by particles of sand, silt, clay, and waterborne debris too large to pass through the small openings of the emitters; particles may also be deposited in the lines, reducing water flow. Chemical clogging is caused by soluble salts that precipitate on emitters as water evaporates from the emitter surface between irrigation cycles. Biological clogging is caused by microorganism growth inside the system. Certain species of bacteria and algae flourish inside drip systems and produce deposits, often of iron oxides, that clog pipes and emitters.

To prevent clogging of the system, some preventive approaches were adopted. An in-line filter was installed to prevent clogging caused by particles; a chemical injector was added to the system for application of acid and/or chlorine at the end of each watering period to deal with chemical and biological clogging. The injector can also be used to fertilize the plants. Chlorination is an effective measure against biological clogging. Sodium hypochlorite solution is the easiest form of chlorine to handle and is most often used in drip irrigation systems. However, excessive amounts of chlorine result in injury to young trees and other plants. Tyson and Harrison (1987) have recommended 5 ppm as an effective concentration. However, sodium hypochlorite increases the pH of water, and precipitation of calcium and magnesium carbonate tends to occur. Bucks, Nakayama, and Gilbert (1979) pointed out that when the pH of irrigation water is above 7.5 and high calcium or magnesium levels are present, carbonates precipitate out either in filters, tubing, or emitters. Therefore, it was decided to use acid, if necessary, to prevent the formation of deposits. Sulfuric and hydrochloric acids are the most widely used.

Layout of the irrigation system

Two water-storage containers were built to supply the system. An 18,000 l semi-underground water tank equipped with a 7-Hp pump located at the riverbank supplies water to a 9,000 l tank equipped with a 3-Hp pump located on-site. Water diverted from the Daquan River flows to a small

settlement pond, then is pumped to the larger water tank. The elevation difference between the two tanks is 50 m, and the horizontal distance between them is about 1,150 m. Connecting the two tanks is steel pipe 5 cm in diameter.

Figure 2 schematically illustrates the layout of the system. The submain pipes are about 15 m long and 100 m apart. A control valve, a Y-shaped in-line filter, and chemical injector are installed at the head of each submain pipe. Each submain pipe is connected to twelve lateral pipes spaced 2 m apart. The lateral pipes are 50 m long and equipped with two emitters every 2 m, spaced 0.6 m apart. Shrubs are planted between the two emitters.

Initially, the experimental area was about 10 m wide and 200 m long. This area was divided into five zones. One species of shrub was planted in each zone. In the fifth zone, the four species were mixed, as a possible means of reducing plant disease. About six hundred, year-old seedlings were planted in six rows and one hundred columns. The spacing was 2 m between rows and columns. To increase wind resistance, the offset between columns was 1 m (Fig. 3).

System design

When designing a drip irrigation system, factors such as water delivery distance, diameter of pipes, type of emitter, and weather conditions need to be taken into consideration. After design criteria are decided, the procedure is as follows:[1]

1. Estimate water consumption per plant per day:
   Liters per plant per day
   = constant × plant area × plant factor × P.E.T. (potential evapotranspiration) / drip irrigation efficiency
   = 10.2 × 2 × 0.45 × 1.143 / 0.75 = 14 l

   Then the total water consumption = l plant^{-1} day^{-1} × number of trees = 14 × 600 = 8,400 l day^{-1}.

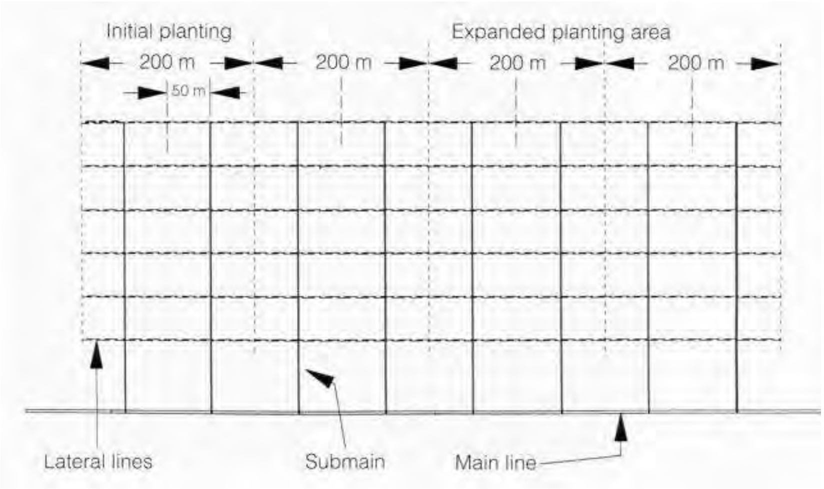

Figure 2
Layout of the system.

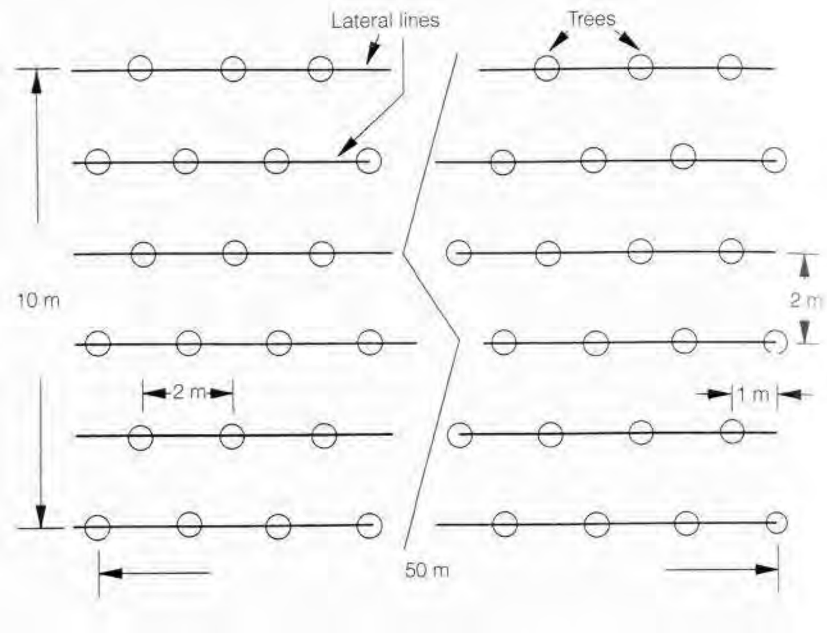

Figure 3
Offset pattern of planting.

2. Determine number of emitters needed:
   Number of emitters per plant
   = area per plant × % to be wetted / area wetted per emitter
   = 2 × 0.6 / 0.65 = 1.85 ≈ 2 emitters

Therefore, this design requires 1,200 emitters.

3. Select emitter type:
   Pressure compensation, single outlet, flow rate 7.6 l hr^{-1}, flow pressure 1.41 kg cm^{-2}, 140 mesh filter.

4. Set emitter running time:
   Hours per day
   = water consumption per tree per day / emitter / flow rate no.
   = 14 / 2 / 7.6 = 0.92 ≈ 1 hour

5. Select pipe size and calculate pressure loss:
   Lateral: 1.5 cm drip tubing
   Pressure loss for 60 m in length and 378 l hr^{-1} is 0.13 kg cm^{-2}
   Submain: 2.54 cm tubing
   Pressure loss for 15 m in length and 4,536 l hr^{-1} is 0.13 kg cm^{-2}
   Main: 5.08 cm steel pipe
   Pressure loss for 1,000 m in length and 9072 l hr^{-1} is 2.67 kg cm^{-2}

6. Calculate other pressure losses:
   Elevation loss: 0.101 × 50 m = 5.05 kg cm^{-2}
   Filter, fitting, and valve loss: ≈ 1.41 kg cm^{-2}
   Safety factor: 1.5

7. Calculate required pump capacity:
   The pressure required to deliver water from source to supply tank is the actual pressure loss multiplied by the safety factor: $(5.5 + 2.67) \times 1.5 = 11.58$ kg cm^{-2} = 115.8 m.
   The pressure required to deliver water from the storage tank to the emitters is $(1.41 + 0.13 + 0.13 + 1.41) \times 1.5 = 4.62$ kg cm^{-2} = 46.2 m.

Pump no. 1

$$\text{Hp} = \frac{1\text{s}^{-1} \times \text{m of head}}{7.61 \times \text{pump efficiency}} = \frac{2.33 \times 115.8}{76.1 \times 0.6} = 5.9 \approx 6$$

Pump no. 2

$$\text{Hp} = \frac{1\text{s}^{-1} \times \text{m of head}}{7.61 \times \text{pump efficiency}} = \frac{2.33 \times 46.2}{76.1 \times 0.6} = 2.35 \approx 3$$

Monitoring Systems and Maintenance

A portable irrometer was used to monitor the moisture content of soil in the root zone at depths of 15 cm and 30 cm. Based on the results, the watering frequency was set at one hour every seven to ten days.

During the watering period, the system and plants are examined. Special attention is paid to evidence of clogging and leakage of the filter, the emitters, and other fittings. Lateral lines and emitters are always covered by sand to extend the life of the PVC tubing. In September 1993, fifteen months after the system was installed, no deposits in the tubes and no deterioration of the PVC tubes were noted. Although it seemed likely, when designing the present system, that the high levels of calcium, magnesium, bicarbonate, and sulfate in the Daquan River water would deposit salts (carbonates and gypsum) on the emitters, such has not been the experience to date. Thus, neither acid nor bleach has been used so far.

As of 1993, the four species of shrubs were growing well (Fig. 4), and the survival rates were *Haloxylon ammodendron* 100%, *Tamarix chinensis* 99.2%, *Calligonum arborescens* 82%, and *Hedysarum scoparium* 94.2%.

Figure 4
Plateau above the Mogao grottoes, showing the growth of vegetation in 1993.

Conclusions

The experimental drip irrigation system described here was implemented in May 1992. By September 1993, only a few plants had died, and these were replaced. The system has been working properly, and no clogging has been reported. These preliminary results are encouraging.

To better evaluate the effectiveness of the vegetation windbreak fence, the experimental area was subsequently enlarged to 800 m in length and divided into four lots. Each lot is 200 m long by 10 m wide. The capacity of the pumping system and the duration of watering for each lot remain the same.

To date, the effectiveness of the vegetation windbreak fence has not been assessed, though when on site, one can clearly observe piles of sand trapped at the base of the shrubs.

Note

1 Formulas for estimated water consumption, number of emitters needed, emitter running time, and pressure loss are derived from Shepersky 1990. Calculation of pump capacity is from Wood 1988.

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Conservation of the Engraved Rock Wall in the Temiya Cave, Japan

Akito Uchida

The Temiya cave is a prehistoric site at Temiya, Otaru City, Hokkaido, Japan. The cave measures approximately 5 × 3 m and is situated about 3 m above ground level under an overhang of a cliff. As a result of excavation by road construction and collapse of the cliff face, the cave today is little more than a recess (Fig. 1).

The Temiya cave is important from an anthropological and archaeological perspective because it contains ancient, engraved characters. In 1866, while prospecting in the cave for stone for building materials, a mason discovered the markings on an inner wall (Fig. 2). In 1920, the cave was designated a national historic site. Excavation research at the front of the cave in 1990 certified the characters as having been engraved about sixteen hundred years ago (Fig. 3).

Generally known as "ancient letters," the characters are also described variously as inscriptions, symbols, and primitive art. However they are interpreted, these engravings are clearly recognized as valuable in terms of cultural heritage (Fig. 4).

Exfoliation and scaling of the cliff rock, a tuff, had become so extensive that it would have been increasingly difficult to identify the

Figure 1
The Temiya cave and its old shelter.

Figure 2
Ancient, engraved characters.

characters if no conservation measures had been taken. The following describes the measures that have been and are currently being implemented for protection of the site.

Geological and Condition Survey

Figure 3
Excavation research.

Figure 4
Photogrammetric plot of the inscribed characters, 1993.

A survey of the geology and condition of the rock was conducted at the Temiya cave in 1986 to obtain information about the geological features in and around the cave and cracks in the character-inscribed surface.[1]

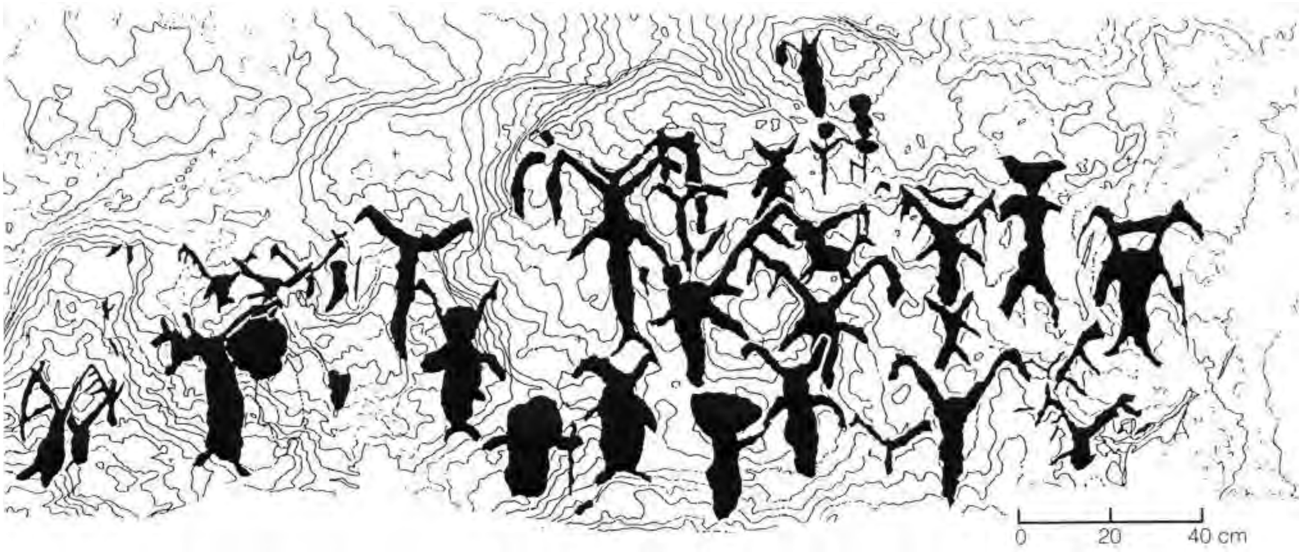
Core samples 9 m long were taken by drilling into the cliff rock at two locations on either side of the existing protective shelter over the cave. Microscopic examination and dye-penetration observations were also carried out to determine the extent of weathering of the rock from the drill-core samples.

To investigate cracks and porosity in the wall surfaces inscribed with the ancient characters, infrared thermography, subsurface radar, and some measurements were made.

Geological structure

The geological material in and around the Temiya cave is classified as the Takashima stratum of the Pliocene. The drilling survey showed the presence of pumiceous tuff to a depth of 2.2–2.65 m and andesitic tuff breccia to a depth of 9 m from that point. The same geological features were found at both of the locations tested.

The pumiceous and andesitic tuffs corresponding to the Takashima stratum form alternating layers, and their distribution is considered to be nearly parallel to the slope surface. The surface on which the ancient characters are inscribed consists of andesitic tuff breccia, which is considered to be different from the geological feature found by drilling to a depth greater than 2.5 m. The andesitic tuff breccia is presumed to be distributed in a lens shape, judging from its relationship to surrounding geological features (Fig. 5).



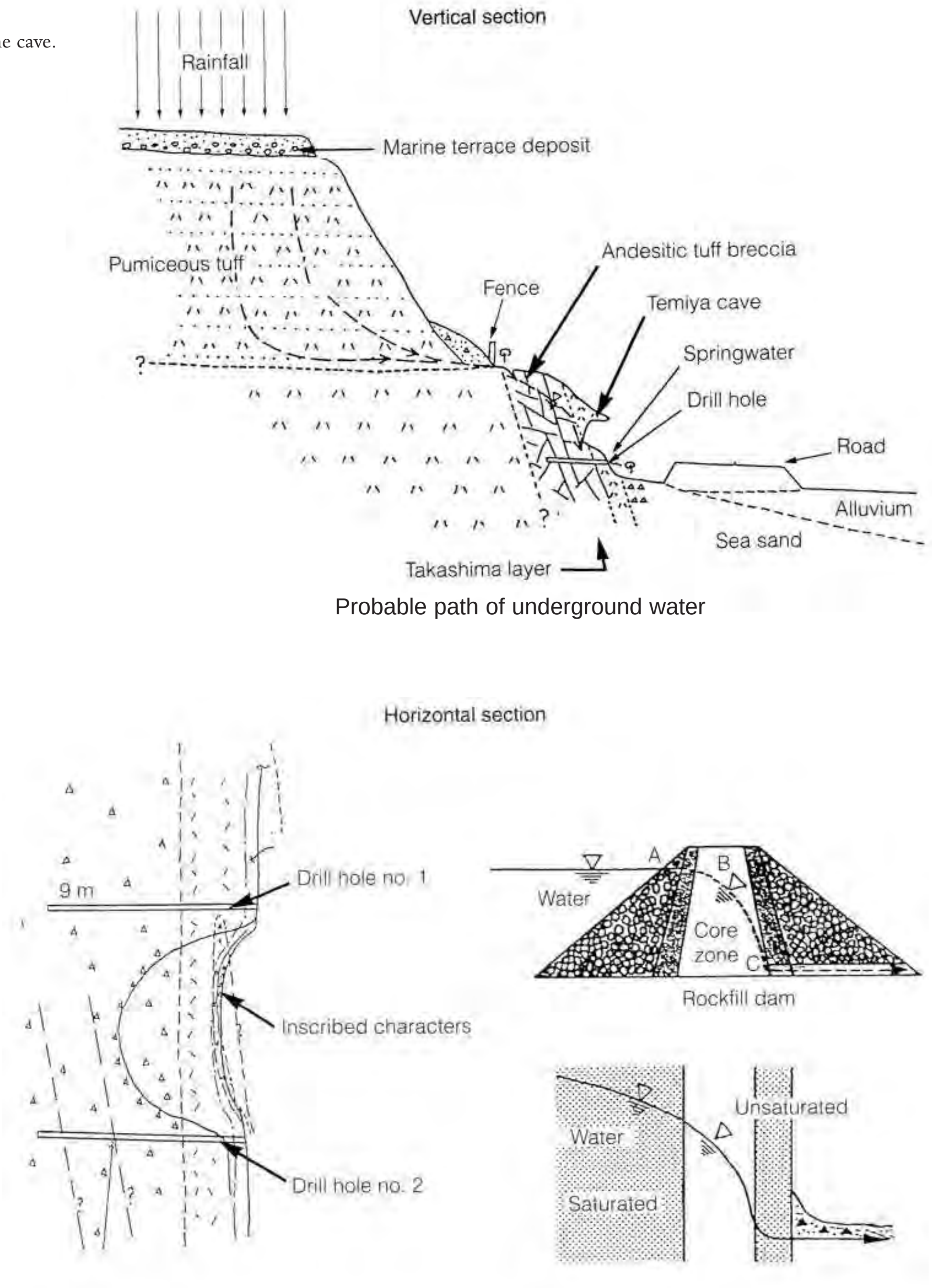


Figure 5
Geological structure in and around the cave.

Cracks in the inscribed rock surface

Open cracks found at the top of the inscribed rock surface seem to occur at the boundaries of portions composed of different types of rock and the andesitic tuff breccia of the character-inscribed surface. The rear side of the crack was thought to be pumiceous tuff, based on its surrounding condition. The result of sonic measurements showed that the open crack is deepest, approximately 90 cm, in the center of the inscribed area, and approximately 25 cm on both sides of the area. The subsurface radar results showed that the left portion of the inscribed area in the center of the wall surface is as thin as 10–15 cm to the reflection surface.

Infrared thermography showed that the temperature of the lower portion of the character-inscribed area is relatively low. This is considered to be due to the fact that moisture seeps from the back of the cave wall, behind the cracks, at the boundary of the pumiceous tuff.

Underground water

The andesitic tuff breccia contains a large amount of underground water in its cracks. The source of this underground water is the rain and snow that falls on the stepped slope of the hill behind the cliff.

It is thought that the moist environment surrounding the general area of the Temiya cave results from the relatively abundant supply of underground water behind the cliff, while the presence of a second weathering zone has formed a wall-surface condition with local moisture near the cave only. This provides conditions conducive to the freezing of water and favorable to biological growth. It is possible that the same conditions that promote this growth also cause biochemical deterioration (Table 1).

Survey of Wall Movement

A survey to measure the annual movement of the inscribed rock face was begun in March 1990. The purposes of the survey were

- to observe movement of open cracks over a period of years by regularly recording displacement;
- to observe the effects on the inscribed rock of vibration by construction work on a new shelter and the effect of conservation work on the cave; and
- to collect basic data for the conservation and repair of cultural sites such as this one in the future.

Table 1 Classification of weathering zones

Depth	0 m	0.5 m	2.5 m	9.0 m
Weathering zone	1	2	3	
Rock property	Pumiceous tuff		Andesitic tuff	
Cracks	Many, open	Very few	Many, degraded	
Leaching	Little	Much	—	
Strength	Low	Low	Low	
Ultrasonic propagation velocity	Low	Somewhat high	High	
Underground water	Unsaturated	Nearly saturated	Present (springwater)	
Fluidity of underground water	—	Low	High	
Porosity of rocks	High	High	Medium	
Water permeability	High	Low	High	
Weathering	Great	Medium	Medium	

Displacement of forward and backward movement of the inscribed rock surface and also of the width of open cracks in the wall's surface was measured. Construction of a new shelter covering an older one was begun in September 1990. Temperature and relative humidity levels were measured inside and outside the new shelter, factors that were believed to be affecting displacement of the inscribed rock and open cracks.

Monitoring instruments could not be installed directly on the inscribed characters because of their cultural value. Therefore, six displacement meters (transducers) with highly sensitive dial gauges were installed at different positions in the vicinity of the inscribed characters. Each of the meters was attached to a specially made magnetic stand with steel legs. The bottom of each leg was fixed to a concrete base (Fig. 6). In addition, nine displacement meters were installed across the open cracks at different points to measure changes in crack width (Fig. 7).

The individual displacement meters were connected to a central monitor (Fig. 8) connected to a personal computer that automatically records the data sent from each of the displacement meters. Measurements are taken four times a day, and the average value constitutes the displacement value for the day.

Monitoring Results

Changes in temperature and relative humidity

Temperature changes in and outside the old shelter throughout the year described an S curve. The outside temperature changed from −4 °C to 25 °C, and the temperature on the rock surface with the inscribed characters in the old shelter changed from −2 °C to 23 °C. This showed that the surface had long been affected by repeated freezing and thawing.

Soon after construction began on the new shelter, and particularly after the outer wall and the roof were completed, the inside temperature

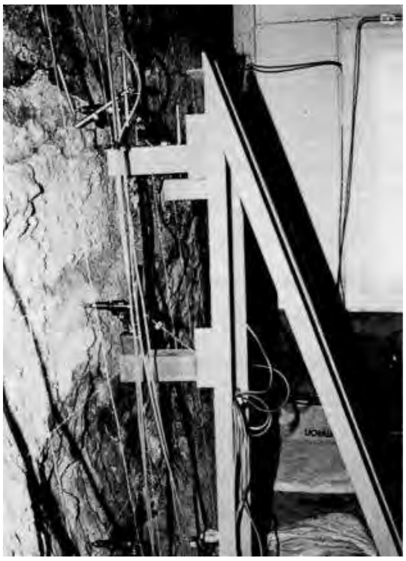


Figure 6
Displacement meters (transducers) installed inside the cave.

Figure 7
Displacement meter (transducer) installed across an open crack.

Figure 8
Displacement monitor shown inside the cave.

did not fall to the same extent as before, and the inscribed rock surface has not frozen since.

In the old shelter (before the new shelter was constructed over the old one), the average relative humidity at the inscribed rock surface was about 80%. Now it is over 90%, as the area is more completely enclosed. The temperature and relative humidity are expected to be properly stabilized with air conditioners after the inscribed rock is covered by a capsule and the interior construction is completed (the new shelter was completed in March 1995).

It is not possible to determine at this time whether the respiration of visitors affects the microclimate on an annual basis, as these measurements have not been made over a long enough period. But such a determination will become possible as the monitoring continues. Measurements will continue for several more years after the environment around the inscribed rock is stabilized in the new shelter.

Contraction and expansion

The inscribed rock surface moves toward the rear of the cave from spring to summer and returns to its forward position from autumn to winter. This movement recurs regularly every year in proportion to the change in temperature, as shown in Figure 9.

Measuring the amplitude of this movement with displacement meters placed at three different points shows that the extent of movement is different at each point. The amplitude is found to be greatest at the upper part of the surface that is exfoliating parallel to the inscribed surface—namely, at the mouth of the crack; and it becomes smaller as it goes deeper.

The effect on the condition and environment of the inscribed rock surface made by the completion of the roof and the outer wall of the new shelter is already remarkable. Since these structures have been completed, the amplitude of backward movement has lessened considerably.

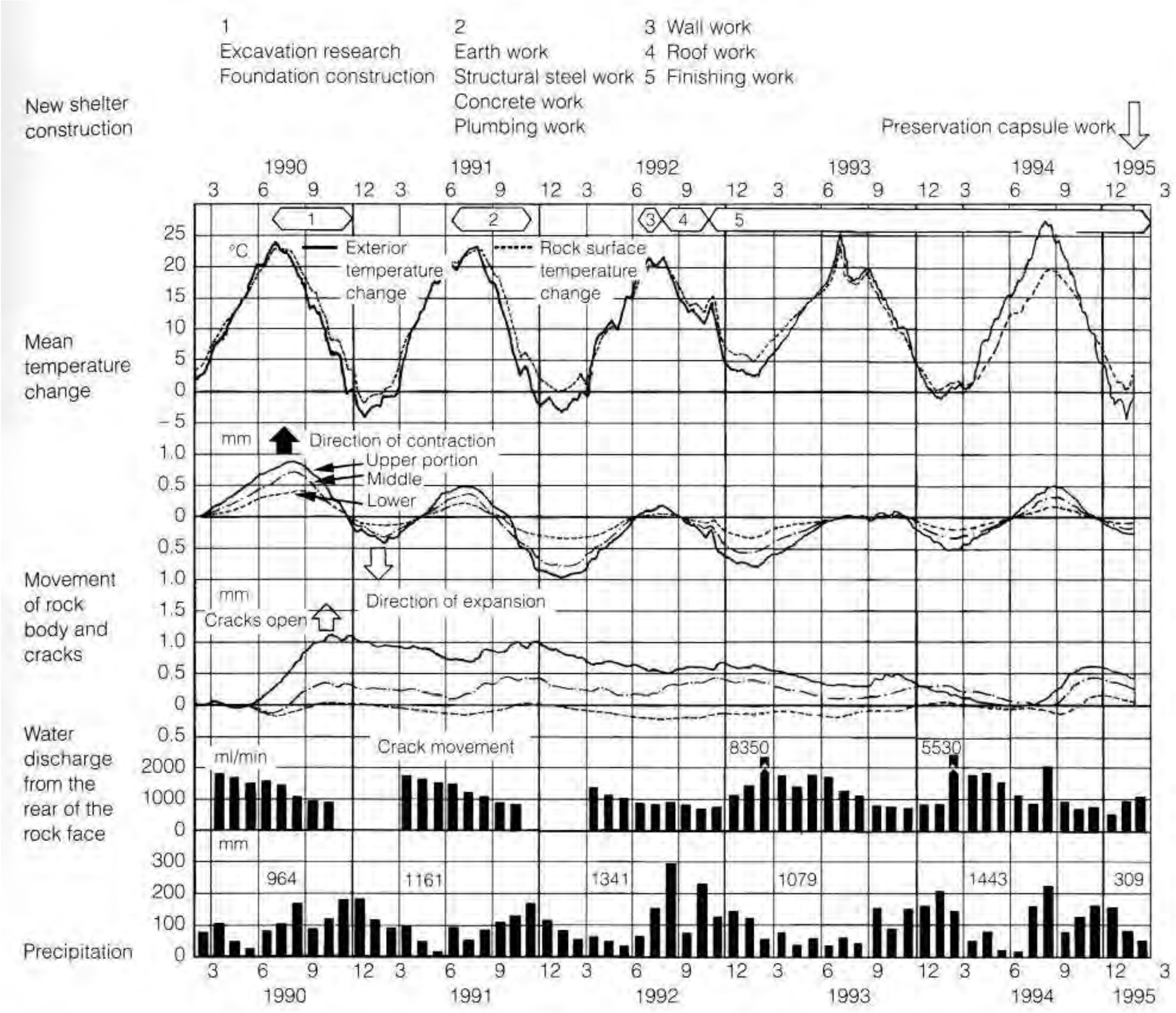


Figure 9
Observation of annual cyclical change. Numbers in bands at top of table indicate stages of new shelter construction and conservation research over a period of five years: 1 = excavation research and foundation construction; 2 = earth work, structural steel work, and concrete and plumbing work; 3 = wall work; 4 = roof work; 5 = finishing work. The arrow at the upper right indicates work on the preservation capsule, which is not yet complete.

Change in crack width

Since the measurement survey began, the width of the open cracks around the characters has become larger, but the degree of change has stayed almost the same. The width of the cracks is expected to become smaller with the completion of the new shelter.

Drainage from behind the inscribed rock

Water is being pumped out from behind the inscribed rock, using the holes made during the core-sample drilling. Drainage volume is measured in milliliters per minute as it gushes out of the pumping holes each month (Fig. 9). Previously, this measurement had not been taken in winter because the water was frozen. The construction of the new shelter, however, has retained warmth and has made it possible to measure pumped water throughout the year. The new shelter has thus had a profound effect on the ability to remove the water that has long been destroying the rock.

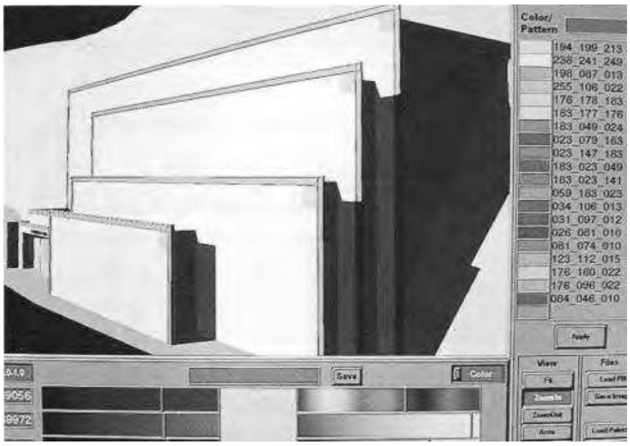


Figure 10
Computer simulation of cave exterior.

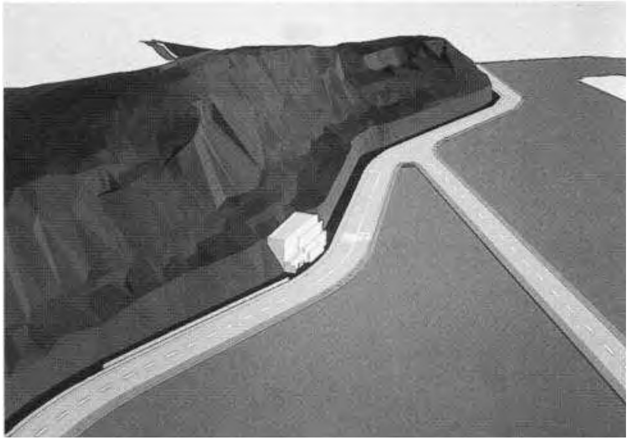


Figure 11
Computer simulation of shelter location and environment.

Figure 12
Computer simulation of shelter interior.

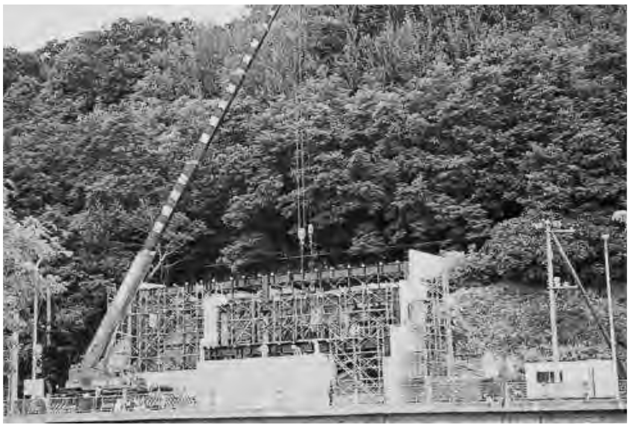


Figure 13
The new shelter under construction.

Computer Graphic Simulation of Surface Conditions

Conditions of the inscribed rock surface were simulated using computer graphics software. Topographical data and information about the conditions of the road running close to the side were based on existing topographical maps on a reduced scale of 1:2500, with data on the new shelter provided by blueprints (Fig. 10). The colors of the exterior of the shelter can be easily simulated by balancing red, blue, and green color values in many different ways on the computer. Different appearances as seen from different perspectives are also possible. Decisions can be made on how to match the shelter with its surrounding environment in regard to color, shape, and a range of other factors (Fig. 11). Many different plans are possible for a shelter's interior design—including colors, displays of exhibitions, lights, preservation capsules, and so on (Fig. 12).

Earthquakes are frequent in Japan, especially Hokkaido, and many people visit the Temiya cave. For this reason, the new shelter was constructed with a steel-reinforced concrete structure (Fig. 13).

Air conditioning installation is underway. To find suitable levels of temperature and humidity, it will be necessary to observe the development of conditions at the inscribed rock face for at least one year.

Note

1 The geological survey was undertaken through an arrangement with Takenaka Construction Company.

Geological Environment of the Mogao Grottoes at Dunhuang

Nobuaki Kuchitsu and Duan Xiuye

Dunhuang is located on the eastern edge of the Takla Makan desert. The average temperature is reported to be 9.4 °C and the average annual rainfall, 32.9 mm.

The Sanwei and Mingsha mountains are in the southern part of Dunhuang Prefecture, where Pre-Sinian (Precambrian) complex rocks are distributed (Fig. 1). On the northern side of these mountains, there are two main fan deposits of the Daquan River, locally called the "old fan" and "new fan" deposits, that cover the basement rock with irregular sediments. The fan deposits and basement rock are both partially overlaid by recent eolian sand, which is one of the threats to the Mogao grottoes.

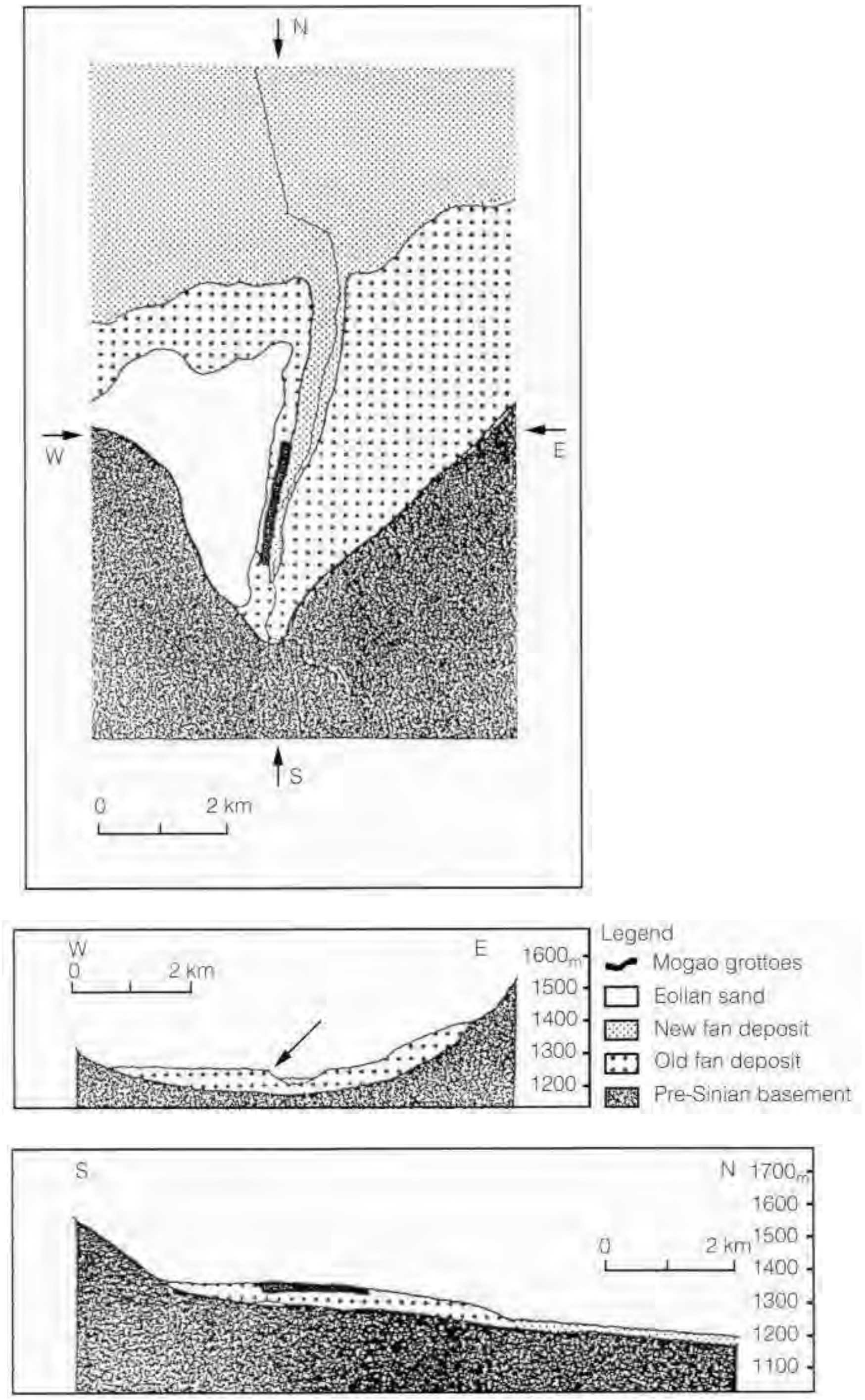
The basement Pre-Sinian rocks are so irregular that they are not suitable for the excavation of grottoes, and the new fan deposit is structurally too weak for digging. Thus, the old fan deposit is the only stratum suitable for the formation of caves in the vicinity of Dunhuang. The Mogao grottoes were excavated into the cliff of the old fan deposit along the Daquan River where the riverbed is deepest (Fig. 1), clearly the most favorable area for the construction of rock temples in the vicinity of Dunhuang.

Salt Crystallization

Salt crystallization is often observed in Dunhuang Prefecture as one of the typical geological phenomena in the desert area. It results from the leaching by water of soluble salts from rock and soil. When the moisture evaporates, crystalline deposits of salts remain. In general, the salt observed at the ground surface is composed mainly of halite (mineral NaCl). When salt crystallizes on the surface or subsurface of mural paintings in the grottoes, it causes flaking of the paint layer. Therefore, it is important to study this process in order to protect the mural paintings from further deterioration.

The approximately five hundred grottoes of Mogao are roughly divided into three groups, based on their location: the higher-, middle-, and lower-level groups. Paintings in the middle-level caves do not show any salt crystallization and are generally well preserved. In contrast, the upper part

Figure 1
Geological map and cross sections in the vicinity of the Mogao grottoes, Dunhuang.



of the paintings in the higher-level caves and the lower part of the paintings in the lower-level caves are often damaged by salt crystallization.

Two of the grottoes have been studied in a collaboration between the Dunhuang Academy and the Tokyo National Research Institute of Cultural Property. These are Caves 194 and 53 (Fig. 2).

Cave 194

Cave 194 belongs to the higher-level group, approximately 29.3 m above the average water table of the Daquan River. In this cave, virtually no

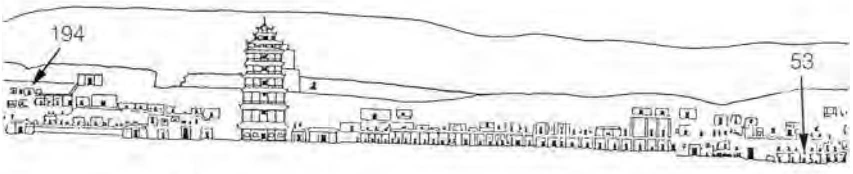


Figure 2
Site map of Caves 194 and 53 (after Sun Rujian).

Figure 3
Deterioration of mural paintings in Cave 194. Salt crystals of approximately 2–5 mm in diameter push up the surface layer and cause the paint to flake.

ceiling paintings remain because of flaking. In contrast, the paintings of the lower part of this grotto are generally well preserved. Observations of the walls indicate salt crystals approximately 2–5 mm in diameter, resulting in flaking of the paint (Fig. 3). The flaking is generally more extensive in the upper parts of the cave because the salt crystals tend to be larger there than in the lower areas.

The salt crystals have been identified by X-ray diffraction as halite, which is also observed in the cementing of the pores of the old fan deposit where Cave 194 was excavated. This cave is located below a slight depression in the plateau above the cliff face, where the influence of rainwater, carrying large amounts of soluble halite, appears to be extreme. Thus, the deterioration of the wall paintings in Cave 194 is the result of infiltration of rainwater through the ceiling of the grotto, followed by evaporation of moisture from the surface, resulting in the recrystallization of the salt and consequent flaking of the paint.

The ceilings and the upper parts of the walls of the higher-level caves at Mogao tend to be damaged similarly to those in Cave 194, presumably through the same process. Therefore, it may be necessary to protect the higher caves from exposure to rainwater, although the average precipitation in the area is no more than approximately 30 mm yr^{-1}.

Cave 53

Cave 53 belongs to the lower-level group, approximately 1.8 m below the average water level of the Daquan River. In this grotto, the paintings on the ceiling and the upper part of the walls are generally well preserved, whereas the paintings on the lower portion are severely damaged or have fallen off. The lower part of this cave had been partially covered with sand, which may be one of the main reasons for the deterioration of the paintings. In addition, salt crystals of approximately 2 mm—some as large as 20 mm—diameter have been observed on the lower part of the walls. Salt crystals in this cave were also identified by X-ray diffraction. Halite was not found, whereas gypsum ($CaSO_4 \cdot 2H_2O$) was identified as the dominant component of the salts in this cave. Although gypsum is a common mineral in desert areas, it is seldom observed in the fan deposits around the Mogao grottoes.

Limestone, which consists mainly of calcium carbonate, is commonly found in the fan deposits and in the paintings' ground layer, or preliminary coating. The main mineral component of the paint ground is not gypsum, however, but calcite ($CaCO_3$). Where, then, did the sulfate ($SO4^{2-}$) ion of the gypsum originate? Certain data suggest an answer to

Table 1 Analytical data of the water of the Daquan River (after Duan [1988] and Kitano [1984])

Samples	Cl	NO_3	SO_4^{2}
Daquan River water	463.19	3.46	824.20
Average river water	7.9	1	11.2

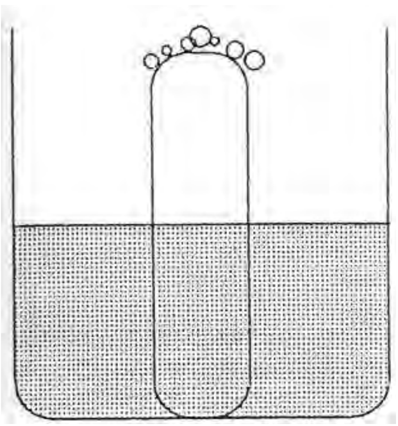


Figure 4
Research on the interaction between river water and the ground layer of paint. A sample of the ground layer of Cave 53 was added to a water sample from the Daquan River. Results show that gypsum crystals form in three days.

this question: Duan (1988) pointed out that the water of the Daquan River has extremely high concentrations of the sulfate ion (Table 1). Therefore, it is thought that gypsum crystallizes when the river water enters the cave and reacts with the paint ground.

An experiment has been carried out to test this theory: A sample of the paint ground of Cave 53 was treated with water from the Daquan River (Fig. 4). Pure gypsum crystals formed on the surface of the ground layer in less than three days. This result indicates that gypsum can be formed rather swiftly in the reaction between the river water and the paint ground.

In 1979, an unusually heavy rain caused flooding of the Daquan River, and the floodwaters entered Cave 53. It is quite likely, therefore, that river water came in contact with primary paint layer in the past to form gypsum. It has not been ascertained whether capillary rise of moisture from soil and rock at the base of the cave has exacerbated the problem, but it is likely that the grotto has experienced floods at least several times during the approximately one thousand years of its existence. Floodwater, therefore, has undoubtedly been one of the principal sources of moisture—with its attendant problems—in this grotto.

The lower areas of the lower-level caves of the Mogao grottoes generally show damage similar to that found in Cave 53. White materials have been observed in some other caves of this stratum that flooded in 1979. It is probable that the white efflorescence is also gypsum that crystallized due to the action of floodwater. Although the Daquan River is ordinarily a nearly dry river, flooding may nevertheless be one of the essential causes of the deterioration of the paintings in the lower caves. Therefore, it is necessary to consider not only the usual environmental conditions but also less frequent natural occurrences, such as flooding, as part of an overall conservation strategy.

Conclusions

Even at the Mogao grottoes, where the average precipitation is no more than approximately 30 mm, rainwater infiltration plays an important part in the deterioration of mural paintings, especially in the higher caves. Floods, which seldom occur in desert areas such as Dunhuang, can also contribute to the deterioration of the mural paintings, especially in the lower caves. Therefore, both typical environmental conditions, such as rainfall, and infrequent natural disasters, such as flooding, must be taken into account in the preservation of this historic site.

Acknowledgments

The authors would like to express their sincere gratitude to all the people who assisted in this collaborative project between China and Japan.

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Geotechnical Stability Problems of the Dafosi Grotto

Gerd Gudehus and Thomas Neidhart

THE DAFOSI (Great Buddha Temple) Grotto, about 200 km northwest of Xian, was completed approximately fourteen hundred years ago. It was excavated in a sandstone cliff by the extension of a natural cavern to about 35 m in breadth, 15 m in depth and 21 m in height. Inside the grotto, three sandstone statues were carved in high relief from the rock of the walls: a sitting Buddha 17.5 m high and two bodhisattvas, each 12 m high. The statues were covered with clay plaster, then painted. The walls and ceiling of the grotto are decorated with hundreds of figures and ornaments carved into the stone. Openings in the partially remaining cliff wall and in the front temple (which was added much later) permit access of light and visitors. Over seventy years ago, a description of the Dafosi grotto was published by Pelliot (1924).

The grotto is currently in dire need of preservation. Parts of the jointed rock ceiling have collapsed, and other parts appear ready to do so. The necks of two statues are cracked and could topple at any time. Immediate support is needed at some points in the ceiling. Sufficient permanent stabilization—carried out with due respect to the monument—should follow. The lower half of the cave temple is seriously weathered from the infiltration of water and salt. Some areas of the ceiling—as well as some of the statues and walls—must be immediately supported, and further deterioration needs to be reduced by stabilization measures.

The geotechnical problems of this grotto and ones like it are rather uncommon, so commonly used tunneling and mining practices are not necessarily applicable.

Geometry

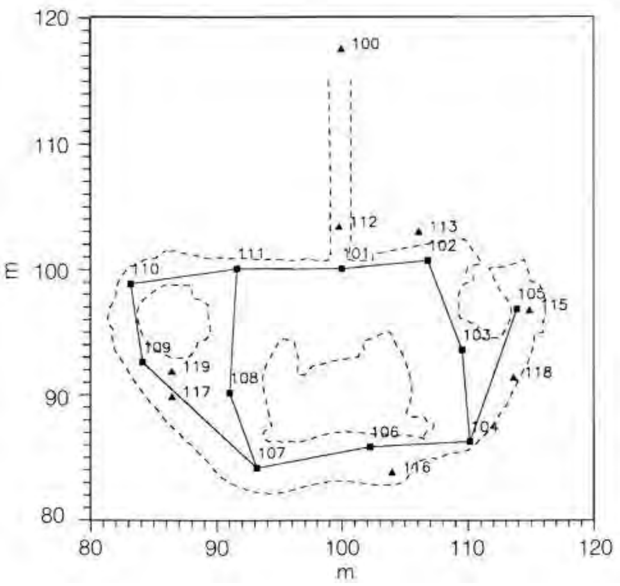
Neither ordinary photographs nor drawings can yield a representation of the complicated spatial geometry of the Dafosi grotto that is sufficiently precise for the geotechnical analysis needed for conservation purposes. While detailed photogrammetric images of the statues have been made, this technique is not suitable for the grotto as a whole. A project supported by the Geodetic Institute of the University of Karlsruhe, with the significant involvement of Manfred Vogel, was undertaken to generate

sophisticated computer graphic illustrations to aid in conservation of the site. As a result, the coordinates of about 6,300 points of the grotto have been determined with an electro-optical total station (Leica and Wild T2002, and DI3000s Rangefinder). The computer graphic illustrations were processed from these data by Neidhart. The software packet AutoCAD Release 12 was used for image processing and computer-aided design (CAD).

To determine spatial geometry, eleven observation points were distributed on the floor, so that almost all parts of the grotto could be surveyed (Fig.1). These, together with five marked reference points at the same level and three at the openings of the temple, formed a sufficient base of reference. The surfaces of the grotto and statues were scanned according to a grid of roughly 0.5 m mesh width; clearly visible marks, such as sharp edges or a change in surface texture, were used. Because of the shape of the grotto and the fact that the statues hide some of the side walls, it was not possible to methodically conduct an exhaustive survey. As a result, some patches of the surfaces of the grotto and the statues were repeatedly surveyed from several points of view. Only small areas (at the shoulders of the statues) remained hidden from every point of view. The data for every point measured consisted of its Cartesian coordinates and a number through which four typical surface types (rock, ornaments, masonry, and weathered fill) were coded. These numbers enabled the scientists to differentiate and color a CAD model.

Vertical coordinates were interpreted from the reference points, a process that yielded forty-one sets of elevation data (0.5 m, 1.0 m, 1.5 m, and so on) with a range of 0.25 m. The coordinates of the whole ceiling, with a wider range, were stored in the forty-first set. Figure 2 shows horizontal cross sections in four elevations that were prepared with these data sets. Figure 3 demonstrates how the same can be done for any vertical section. Other sections of this kind can easily be made so a rough impression of shape, size, and relative orientation can be obtained.

Figure 1
Survey reference points. Points 112 and 113 are in the openings on the first floor of the front temple.



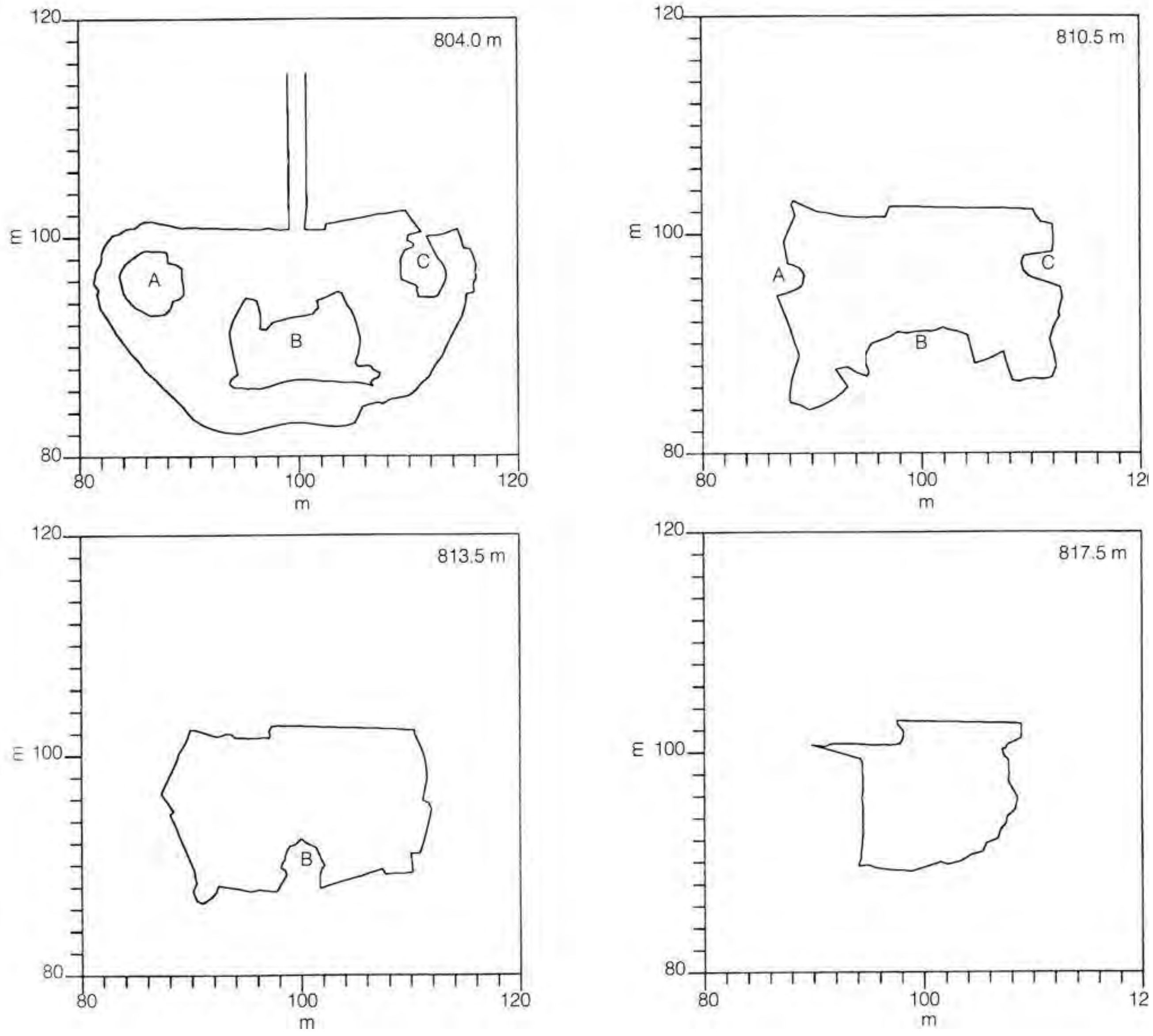
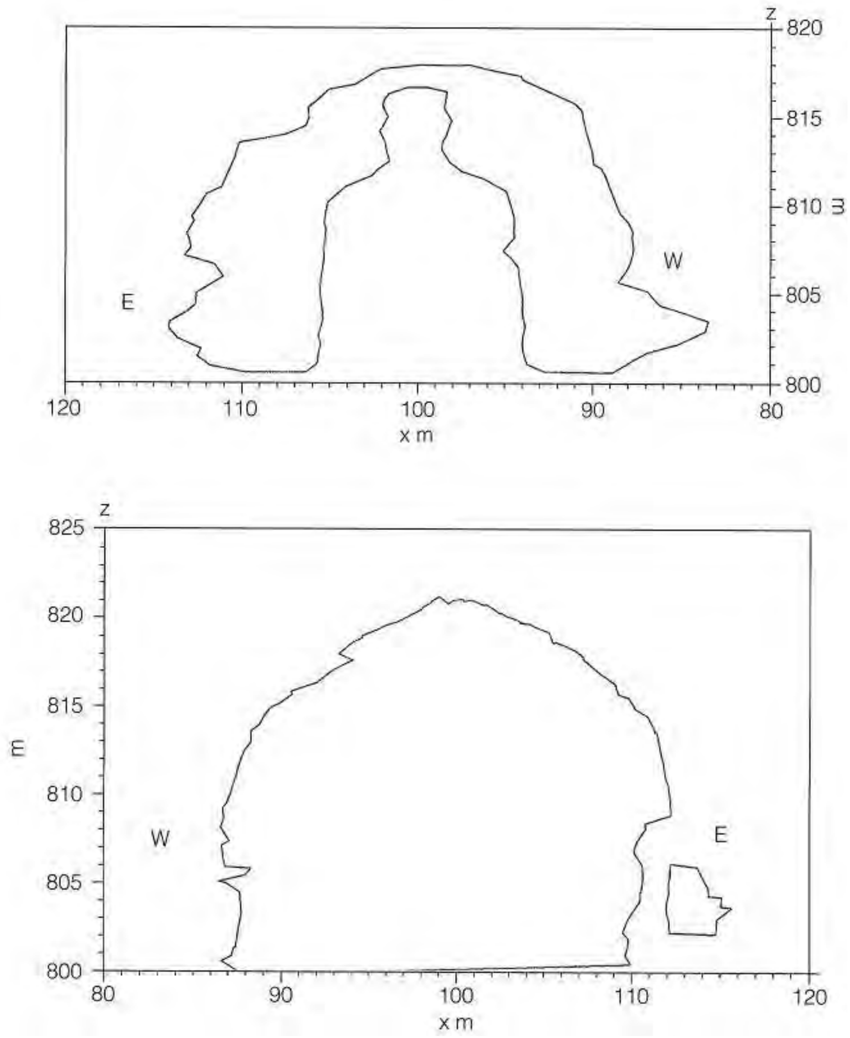


Figure 2
Horizontal cross sections at four elevations above the grotto floor with letters indicating the statues, as follows: A = Bodhisattva Avalokiteshvara, B = the Great Buddha, C = Bodhisattva Mahastamaprapta.

It is much more difficult to generate a complete spatial impression of the grotto with computer graphics. The problem lies in the concavity of the surfaces, the possible loss of specific detail, and the omission of hidden parts that might be necessary to fully model the chosen point of view. As standard procedure, the points in every data set were rearranged to unify the sense of rotation (in a right-handed Cartesian coordinate system), which is necessary for the CAD software to generate surfaces with normal vectors extending from the surfaces into the grotto. Finally, every data set was split according to the change of materials, corners, and edges, to prevent the CAD software from producing any smoothing of these significant parts of the grotto. The points of each subset were interpreted by the CAD program as three-dimensional polygons connected with rectangular surface patches.

Figure 4 gives a rather complete impression of the grotto except for the remaining cliff wall and the front temple, which are omitted. The

Figure 3
Two vertical cross sections.



sitting Buddha fills the grotto almost to the ceiling. The two bodhisattvas are leaning toward the walls and are clearly subordinate. A kind of circuit surrounds the statues near their bases. The grotto surface is roughly shaped as one-quarter of an ellipsoid. Convexities of this surface carry decorative parts, such as the Buddha's halo. Concave parts are largely the result of losses from rupture in the upper half of the grotto and erosion in the lower half.

Figure 5 shows another image of this kind. The observer's point of view can be chosen arbitrarily, and various parts of the CAD model can be removed to achieve a better perspective. The images have been enhanced with shadows and colors to strengthen the spatial impression. It is evident that photographs and videos are needed to obtain more detailed pictures, but these can be far better understood with the aid of the CAD images. These graphics form a substantial part of the authors' geotechnical reports; they are also useful in the authors' own work and in collaborating with other scientists.

Upper Half of the Grotto

Toward the ceiling of the grotto, the rock is almost pure sandstone, rather dry, and as permeable as fine sand. It has an old system of fissures, typical

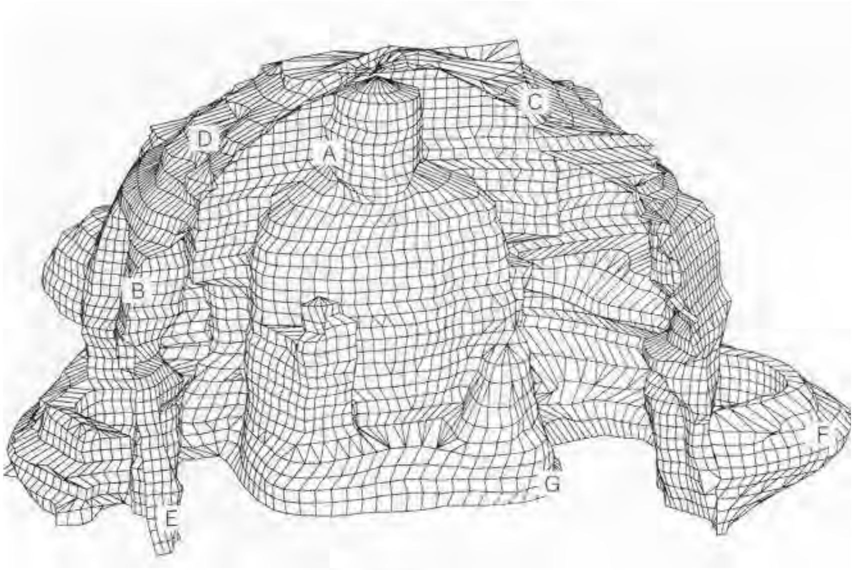


Figure 4
Unshaded CAD model. Point of view from the northeast. Letters mark vulnerable parts of the grotto surface and statues: A = head of the Great Buddha, B = eastern bodhisattva, C = ceiling to the left and in front of the Buddha, D = area of dangerous "coffin lids," E = foot of the eastern bodhisattva, F = circuit behind the statues, G = base of the Buddha.

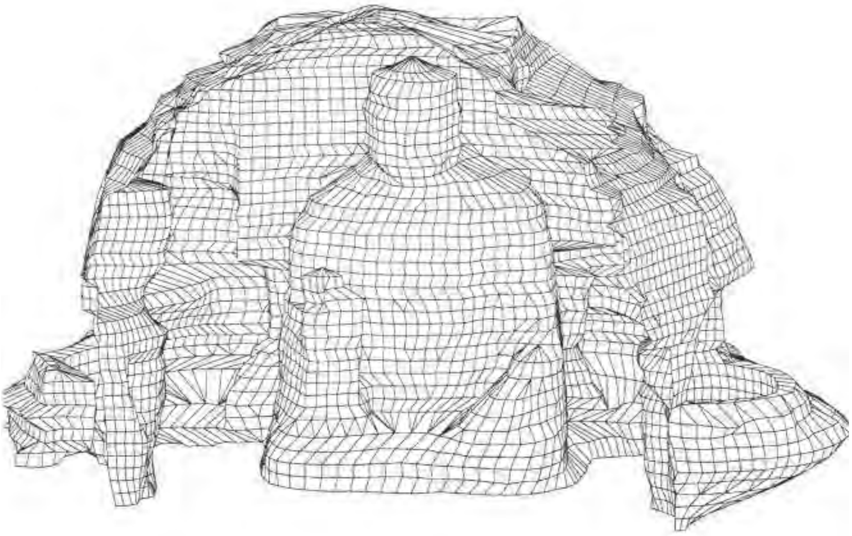


Figure 5
Unshaded CAD model. Point of view from the north.

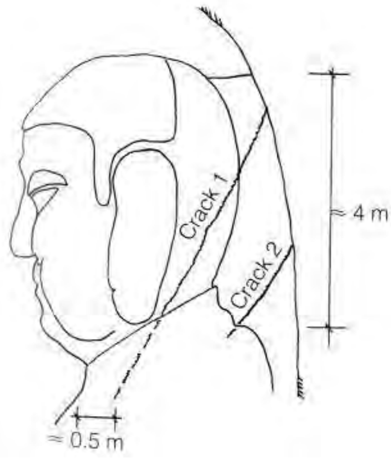


Figure 6
Cracks at the Buddha's head with an inclination of approximately 60°.

of cliffs, which can be seen from the outside. These cracks have extended and opened as the stress release along the grotto surface has produced stress concentrations close to the cracks. Also, the cracks tend to expand with time as a result of reduction of strength caused by weathering, temperature changes, and occasional dynamic impacts. The rubble on the floor indicates that, over time, substantial parts of the former ceiling collapsed long ago, but it is not possible to determine from below which parts are likely to fall next. A scaffold has therefore been erected; from it, close inspection of the whole grotto surface and the statues was conducted by Zou Yazhou of the University of Hydraulic and Electric Engineering in Wuhan. The inspection revealed a far more dangerous situation than had been expected. Vulnerable portions are labeled in Figure 4.

The Buddha's head (Fig. 4, area A) has two visible parallel cracks that extend from the back almost to the chest (Fig. 6). They can barely be seen from the floor, and an even closer view does not fully reveal them because of the clay-plaster cover. Measurement of the attenuation of weak

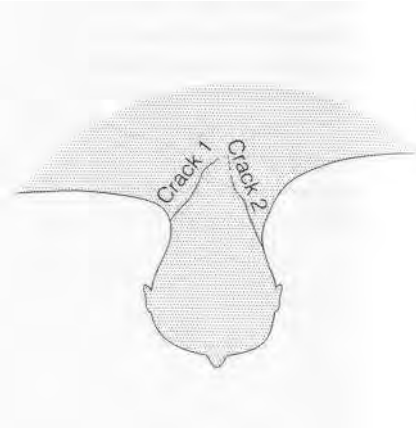


Figure 7a, b
The head of the eastern bodhisattva (a) showing location of a visible crack; and (b) horizontal cross section through the head of the bodhisattva, showing existing cracks and their expected development.

Figure 8
View of the Dafosi grotto, showing rock outcrops (upper right) in ceiling area to the left of the Buddha.

shock waves reveals that the two cracks pass through the stone horizontally. It can also be seen that part of the cracks appear to be fresh and thus are developing. Indeed, the head will eventually break off when the cracks are sufficiently deep. The eastern bodhisattva, on the right side of the Great Buddha, has a similar weakness: the head is partly separated from wall and body by two cracks (Fig. 4, area B; Fig. 7a). Only one crack is visible from the floor, and only a very close inspection revealed the danger presented by the second one (Fig. 7b). As the head is inclined toward the Buddha, it is likely to fall in this direction.

The ceiling to the left and in front of the Great Buddha (Fig. 4, area C; Fig. 8) contains a few very loose protruding blocks with masses of up to about 50 kg. One of these blocks fell in 1992; this dangerous event led to the decision to erect the scaffold and conduct a close inspection. Other very loose small blocks, previously unseen, were then identified from the vantage point of the scaffold. Because their documentary value appeared low relative to the cost of stabilizing them, they were removed immediately.

Close inspection itself posed a high risk. A very dangerous area was discovered to the right of the Buddha's head (Fig. 4, area D). In that spot, orthogonal patterns of joints almost permit the separation and falling of a series of slabs or plates weighing about 2 t each (Fig. 9). Gentle tapping applied experimentally to these plates caused them to vibrate with a low frequency—an indication that the plates are attached on only one side. The term "coffin lids," used by miners for such slabs, indicates the danger they pose.

The authors, together with Ge Xiurun of the Academia Sinica in Wuhan, conducted a detailed stability analysis and designed proposals for stabilization. The two bodhisattva heads will be temporarily secured by

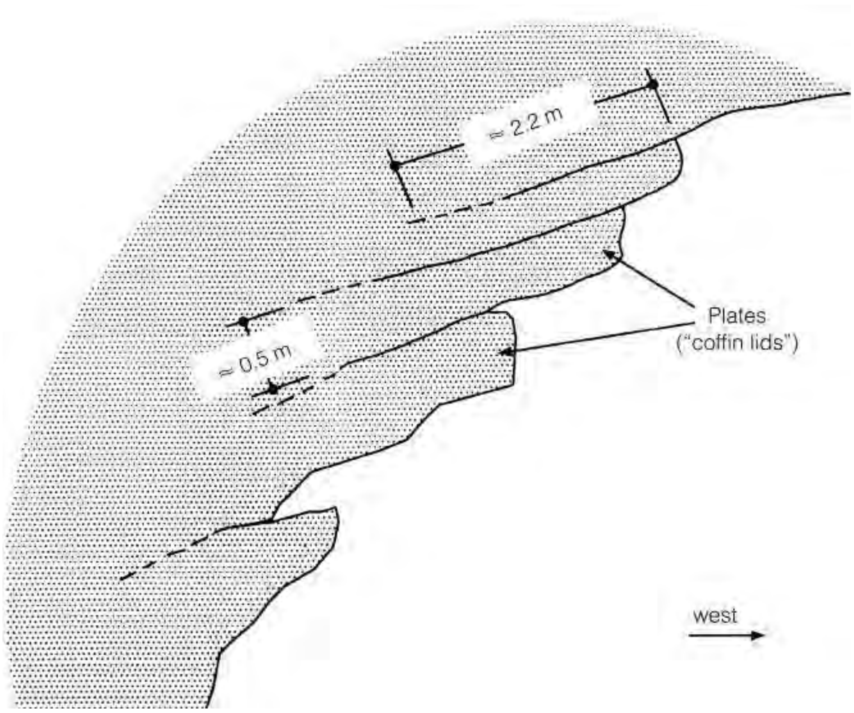


Figure 9
Vertical cross section through the ceiling and head of the eastern bodhisattva, showing the dimensions and shape of the "coffin lids."

steel brackets traversing the cracks. The use of small-diameter drill holes with interior application of glue is an acceptable intervention, considering the otherwise high risk of loss. Subsequent long-term stabilization will require bolts placed nearly vertically with reference to the cracks; it is possible that filling the cracks with mortar would worsen the situation. Respect for the statues precludes bolting their heads from the front; instead, holes must be drilled from behind or from the sides. There is a narrow cavity behind the Buddha's shoulders that should permit drilling. Holes drilled from the side at appropriate angles can reach the cracks behind the bodhisattva.

For this type of repair, stainless steel or fiberglass bolts will be placed into the drill holes (Fig. 10a). Filling the holes with compacted sand (Fig. 10b) and prestressing the bolts with screw nuts (Fig. 10c) will achieve the necessary static contact (Fig. 10d). This type of rock anchor, which was developed at the Institute of Mining of the Russian Academy of Science in Novosibirsk (Stashevski and Kolymbas 1993), is strong and durable. It is also chemically neutral and therefore reversible from a conservation standpoint. The anchor system was further developed at the Institute of Soil and Rock Mechanics in Karlsruhe and tested on sandstone blocks, including overhead installations. Field tests have also been performed on this anchor system in soil—for example, in the stabilization of retaining structures. The installation of anchor systems combining bolts and sands has been extensively and successfully achieved under various conditions (Gudehus 1994). In Bulgaria, such sand anchors have been used to fix rock blocks in steep slopes in cases where they threaten to destroy historic buildings (Stashevski and Kolymbas 1993).

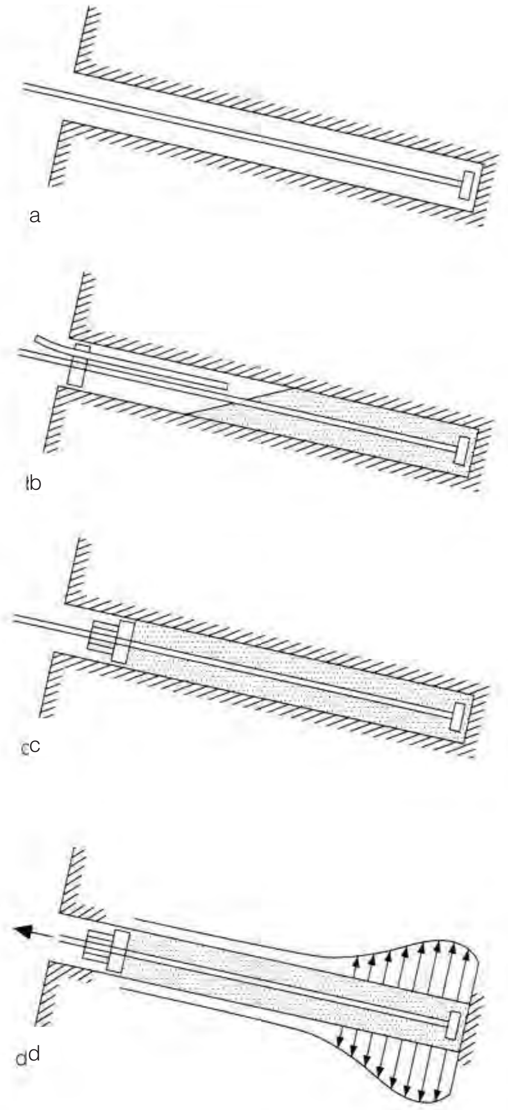


Figure 10a–d
Schematic drawing, showing installation of a sand anchor in rock.

Before applying rock anchors at the Dafosi grotto, the coffin lids require temporary props; otherwise they cannot be touched. Of course, the floor below them must be closed off. Drill holes with bolts and sand, such as those used for the heads of the statues, have been prepared and will be prestressed so as to carry the entire weight of the rock plates.

Ge Xiurun is analyzing the stability of the upper half of the grotto using a finite element method to calculate the stresses caused by the excavation of the grotto and to estimate stresses that may be caused by future earthquakes. These calculations will aid in identifying zones of impending rupture. A further, more detailed but protracted calculation was made for some cracked areas of the ceiling. These calculations are more difficult to carry out than are similar ones currently used in rock mechanics for the analysis of storage dams and rock cavities.

Consideration has been given to the placement of monitors to signal an impending rockfall. These monitors are desirable because an accurate mechanical analysis of stability is beyond the scope of present geomechanical calculations. An indicator of insufficient stability is an

increasingly abnormal wave transmission and emission behavior. Even though this relationship is qualitatively known in mining and earthquake engineering, a consistent mathematical predictor is not yet available. Therefore, at the present time, intuition based on experience is the best guide.

Lower Half of the Grotto

Toward the bottom of the grotto, nearly horizontal layers of clay are embedded in sandstone. Seepage of moisture from the loess cap of the sandstone formation migrates above the clay toward the cliff wall in the grotto. Capillary rise of moisture is nourished by this horizontal flow and strengthened by evaporation along the wall of the grotto. The lower half of the sandstone is wet, and water content decreases toward the ceiling. Dissolved salts, which migrate in the capillary water, crystallize at the surface to develop a white efflorescence. Part of the salt crystallizes below the stone surface; the resultant expansion has produced spalling of parts of the rock surface. In principle, this mechanism of weathering is well understood in geology and in the deterioration of monuments. Nevertheless, it is very difficult to analyze the process precisely and prevent further deterioration by technical means.

Such defects, caused by salt crystallization in the stone, can be seen in other areas of the grotto shown in Figure 4. Part of the foot of the eastern bodhisattva (area E) has been lost, and the entire statue could break down in the near future. The circuit behind the statues (area F) is expected to enlarge, causing the rock above to lose support. The base of the Great Buddha (area G) has become so soft that parts of it have already crumbled away. It is now inadequately supported by a buildup of sediments from the river and by rock material from the grotto.

Even without an analysis of mechanical stability, it is clear that this weathering will completely destroy the lower part of the grotto and the statues over the course of time. Some parts—as, for example, the right side of the Great Buddha's halo—are already approaching collapse and require immediate support. Disintegration of the rock face must be stopped or at least reduced.

One remedy to these problems, theoretically, would be to interrupt or reverse the flow of water and dissolved salts into the grotto. This step is not practicable, however, because surface layers would spall off after some time; drainage holes would divert only part of the seepage water; and vacuum or electroosmosis methods are not reliable for sandstone.

It will therefore be necessary to tolerate an ongoing influx of water and salts into the grotto. But further damage can be reduced with sacrificial plaster layers, sometimes used for the conservation of buildings. In this scheme, transported salts accumulate on and inside the layer and do, indeed, eventually destroy it—but the layer can be easily replaced later. Tests have been made in Karlsruhe, in cooperation with visiting Chinese scientists, to demonstrate the use of sacrificial plaster layers in combating salt transport.

Various means of supporting endangered features of the grotto were studied. Strengthening the interior by injection or reinforcement was

rejected as too dangerous; and the long-term behavior of these methods with very soft rock is unpredictable. The surface installation of metal and synthetic supports was also rejected as incompatible with the appearance of the monument.

A decision was made to employ masonry to support parts of the Buddha's halo and thereby also cover the scars of erosion. A brick wall for support had already been erected to the left of the eastern bodhisattva, but it was considered inadequate because of the incompatible surface and the deviation in shape from the original wall. The new supporting masonry will be made of sandstone blocks joined with a small amount of compatible mortar, so the facade will resemble the former grotto surface. Areas of the grotto affected by substantial amounts of water containing dissolved salts will receive a surface coat of sacrificial plaster.

The bottom fill will be removed to return the grotto to its former level. This will be done in small, careful steps, to secure historically important inclusions, as well as to maintain stability. The excavation is being performed under the direction of archaeologists. Only narrow pits have been excavated, so the remaining parts can still provide sufficient support. The supporting masonry will be placed on firm ground and built up to the intact rock surface. At some points, it will be necessary to connect the masonry to the rock behind it by the use of bolts with sand, as described.

Acknowledgments

The conservation of the Dafosi grotto is the aim of a collaborative project undertaken by the Ministry of Cultural Goods in Xian and the Bayerisches Landesdenkmalamt in Munich. The support of the project by the German Ministry for Science and Technologies is gratefully acknowledged, along with that of the Geodetic Institute of the University of Karlsruhe, and the work of Manfred Vogel. Geotechnical work was substantially supported by the following Chinese colleagues: Ge Xiurun of the Academia Sinica in Wuhan; We Wei of Xian Technical College, now working with a German company; and Zou Yazhou of the University of Hydraulic and Electric Engineering in Wuhan, working at the time of this writing with the authors in Karlsruhe.

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KEYNOTE ADDRESS

Conservation of Subterranean Historic and Prehistoric Monuments

The Importance of the Environment and Microclimate

Jacques Brunet, Jean Vouvé, and Philippe Malaurent

The prehistoric decorated caves found in France, formed by the weathering of calcareous rock, are generally the result of morphological, structural accidents. Before they were found, these caves were either totally isolated from the outside world or, in some cases, discernible only through tiny fissures or openings. Environmental conditions maintained over long periods of isolation—several thousand years in the case of some upper Paleolithic caves—have determined what types of rock art remain visible today.

Following the discovery of these caves and the greater appreciation of prehistoric art they engendered, access to them was provided by cutting openings through blocks of fallen or crumbled rock that had built up over the millennia. This new access has disturbed the caves' natural, subterranean environment, which had remained stable prior to intervention, and has also disturbed the rock art they contain.

The purpose of the following discussion is to explore the requirements for conserving natural, subterranean sites and to apply the results of these investigations to specific examples. It is hoped that knowledge gained by studying carbonate rock might also shed light on the problems of tombs, tumuli, and other subterranean natural, prehistoric, or historic monuments.

Factors Affecting the Stability of Paintings and Engravings in the Subterranean Environment

The atmosphere

Like aerial space, subterranean space has its own defined character. Its internal climate can be influenced either directly or indirectly by the external climate. Variations in temperature, atmospheric pressure, environment, and different density levels of the interior space generate air movement and exchange with the exterior. The exchange in both directions takes place either continuously within the atmospheric domain or more indirectly through the porous and permeable geological matter, such as the cave rock itself, fallen rocks, earth, or karstic infilling. The atmosphere of a cave or buried monument is established by its geomorphology,

position, and depth in the ground (Schoeller 1972; Vouvé et al. 1983). Depending on the surrounding natural context, the cave may be subject to air exchanges, both thermal and hydrogeological, that emanate from the surface but take some time to diffuse. When a cave is superficial (extending less than 25 m into the ground), temperature differences and variation in air flows may depend on the following:

- general layout of the cave entrance (morphology, exposure, altitude);
- geometry and nature of any geological aquifer or reservoir in relation to the subterranean space; and
- geometry of the cave space itself (horizontal, descending, or ascending).

One recent and very important consideration is the effect of tourism on ancient decorated caves. Studies have shown that each visitor introduces 40 g of water vapor, 20 l of CO_2, and 250 J $hour^{-1}$ into the subterranean environment. These moisture, gas, and thermal intrusions destabilize the interior environment of the cave. Visitors also introduce the risk of biological contamination by microorganisms, such as algae, bacteria, and fungi, which grow rapidly in a subterranean environment. Mineral salts and organic matter are other problems created by the respiration and transpiration of visitors, who also produce a dust layer on the wall surfaces as they walk across the ground.

To this list of tourist-induced hazards may be added the increased exterior-interior air exchanges that take place as visitors come and go, and the effects of heating from artificial lights, which are constantly in use during tourism periods.

Cave rock

Bare rock provides the support base for decorated cave walls, the surfaces of which have been formed and shaped by natural erosion. In general, the limestone or sandstone rock has not been modified by tools or mortar. A consideration of the physical characteristics of the rock—its cracks, water content resulting from direct or delayed infiltration, and chemical qualities (such as salt and mineral content)—should influence the decisions made in conserving a subterranean environment.

Location of paintings and engravings

Painted and engraved rock art is situated at the interface between rock and air, and it is affected by the physicochemical mechanisms that develop there. Thermal exchanges with the interface (rock-water, rock-air, air-water) and dynamic exchanges between the exterior and subterranean environments cause water and air migration into underground caves that, in turn, produce condensation or evaporation. In limestone caverns, all these mechanisms have both favorable and adverse effects on calcite formations.

The mechanical stability of a cave's inner walls and decorations (as well as the surfaces of most archaeological objects) is dependent essentially on humidity level. A sudden and significant dehydration of the surface will impair the cohesion of pigments and mortar. In the same way, significant condensation will form a permanent water film, which fosters the development of harmful bacteria and algae. Condensation trickling down a wall's surface eventually leads to deterioration and loss of paintings and decoration.

Given these conditions, safeguarding the subterranean environment with its art and artifacts requires nothing less than actual atmospheric control, with tourist visits limited to five persons per day.

Evaporation-Condensation and Conservation of Subterranean Environments

Only a few environmental parameters can be measured with certainty:

- temperature of the external air
- relative humidity of the external air
- atmospheric pressure of the external air
- temperature of the air inside the space
- relative humidity of the air inside the space
- atmospheric pressure of the air inside the space
- temperature of the inner wall surfaces

The air mass of a cavity of temperature T_a, in contact with the inner wall of temperature T_p, is subject to the physical laws of condensation and evaporation. Thus, when the air's water-vapor pressure is greater than its saturated water-vapor pressure (at the same temperature as the wall surface), a film of water will appear as a result of condensation. Characteristics of this wet film vary, depending on the air mixture at the wall surface, the makeup of this surface, and its porosity. Unfortunately, these factors are almost impossible to calculate. Likewise, if the air's water-vapor pressure is lower than the saturated vapor pressure (at the same temperature as the wall surface), water will evaporate from the wall. How will this condensation and evaporation affect the support surface?

In climates where rainfall lasts from a few weeks to several months of the year, the water exchange (vapor-liquid) within the heart of the rock and at the interface with the atmosphere leads invariably to deterioration. The problem of evaporation-condensation and the response this causes on the interface is the main issue here (Stefanaggi, Vouvé, and Dangas 1986; Malaurent, Vouvé, and Brunet 1993).

In each of the following examples, droughts, intense rain, or other exceptional weather patterns—as well as structural work—are at the root of the microclimatic processes. These conditions cause an imbalance between the water-vapor pressure in the air and at the interface, resulting in either a physical or a physicochemical reaction on decorated and undecorated surfaces. In the following case studies of moisture imbalances, A and A′ refer to decorated caves and shelters; B refers to archaeological sites (Fig. 1).

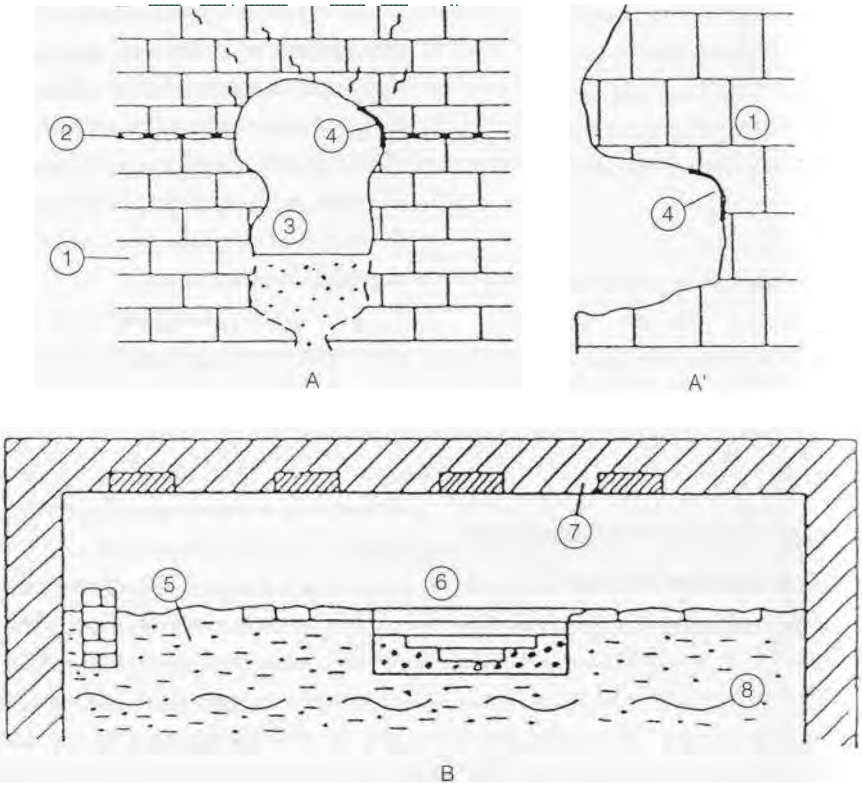


Figure 1
Caves (A), decorated shelters (A′), and covered archeological sites (B) all have their own particular microclimate: 1 = calcareous fissures; 2 = impermeable calcareous clay; 3 = sand infilling; 4 = paintings; 5 = sandy clay alluvial deposits; 6 = archeological objects; 7 = alveolar concrete vaults; 8 = water table.

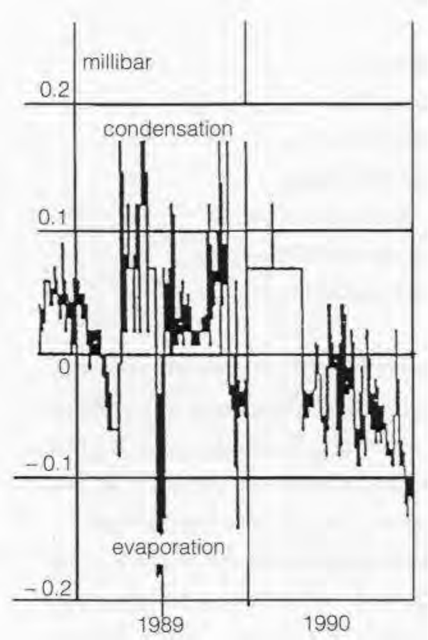


Figure 2
Diagram showing evaporation-condensation phenomena in the case of a cave; analysis was carried out between 1989 and 1990.

The first three examples present cases in which the water-vapor pressure at the carbonate (or similar type) wall surfaces is greater than the more balanced pressure of the surrounding air.

Cases A and A′: Cave or rock shelter

In a cave or rock shelter excavated in limestone, water that is present at the interface (in the form of a film or droplets) and that is in chemical equilibrium with the calcitic facies will evaporate (Fig. 2). This calcite formation takes place under a variety of polymorphic conditions, the main micromorphologic patterns of which are shown in Table 1 (evaporatory conditions). An example of needles grafted onto preformed buds is shown in Figure 3. Methods used to obtain visual images and automatic

Figure 3
Growth of calcite crystals on a prehistoric painting.

Table 1 Identification of growth and dissolution of calcite crystals influenced by evaporation-condensation phenomena, as seen in decorated caves or shelters

Growth phase (polymorphism) (evaporatory conditions)	Dissolution phase (condensation conditions)
• Single (pinpointed), clusters, larger areas precipitates: amorphous	• Forming of craters or pits (craterization)
• Simple, complex growth (chaotic, massive)	• Ablations (tips of needles and microdroplets)
• Needles grafted onto flat or "conchoidal" supports	• Flaking
	• Swellings and loss of cohesion
• Pointed budding disorganized, organized, thin layers, flakes	

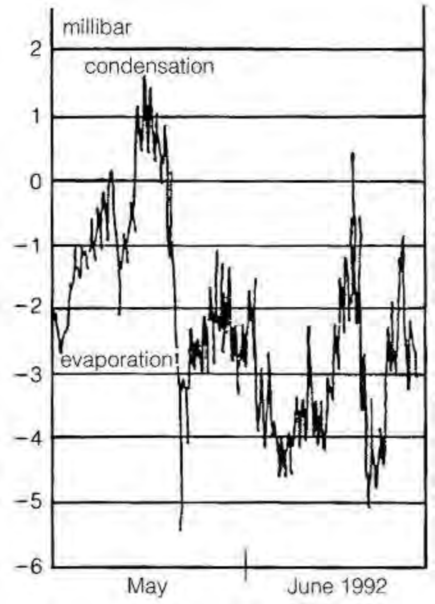


Figure 4
Diagram showing the evaporation-condensation phenomena in the case of an artificially covered archeological site. Analysis was carried out in May and June 1992.

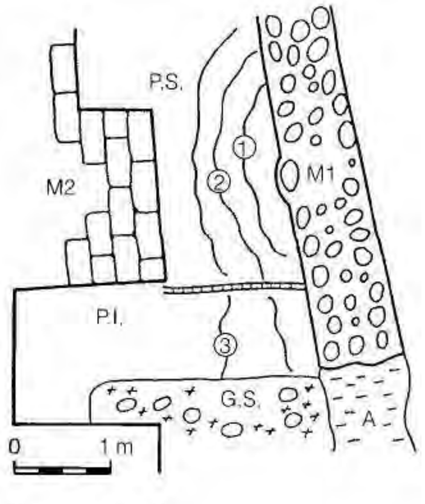


Figure 5
Ground plan of the excavation: P.S. = higher floor; P.I. = lower floor; M1 and M2 = eroded historic walls; A = clays; G.S. = shingle. Map of the observed increase of the bleaching area (salts) at different periods of time: line 1 = 31 March 1993; line 2 = 1 June 1992; line 3 = 22 September 1992. Lines 1, 2, and 3 are the limits of the bleaching area.

processing of these data make it possible to follow the phenomena of crystal growth stage by stage.

Case B: Burial vault

In a monument such as a concrete burial vault with the same evaporatory atmosphere as a cave (Fig. 4), the saturated or capillary water content of the walls' stone or mortar (or other porous or permeable archaeological elements) migrates toward the interface where it eventually evaporates (see Fig. 5, walls M1 and M2). This phenomenon sometimes includes chemical precipitates and often entails loosening of mortar, joints, and other coatings. It is also often accompanied by flaking, powdering, and bleaching of the colored areas, which may be made up of crushed and compressed brick. In Figure 5, the effects (bleaching) of water evaporation are shown coming from the walls (M1 or M2) through the floor.

The next three examples represent cases in which the water-vapor pressure of the wall surfaces is lower than that of the surrounding air. In A and A′ (cave or rock shelter), the water vapor of the subterranean atmosphere condenses on the surfaces and/or the calcite formed on the vaults of an enclosed space. Continual condensation over the years (Fig. 2) has created a constant supply of water, thousands of microscopic droplets that enlarge and merge. Methods used to obtain visual images and automatic processing of these data make it possible to identify these droplets, especially when they appear on a painted support (Fig. 6). Depending on the calcitic micromorphology, the interaction of these droplets with each other may lead to water flow. This, in some cases, leads to leaching loss and dispersion of organic (wood charcoal) or mineral pigments in wall paintings. Preventive measures are essential if the wall paintings and rock art are to be conserved. It is also important to note that in situations where the wall is homogeneously wet, without flowing, the effect of the film of water increases the visibility of the painted layers.

Case B is an example of an urban archaeological site with wall constructions and overlapping flooring built on fine silt, sandy clay, and coarse gravel alluvial deposits that are extremely close to the middle level

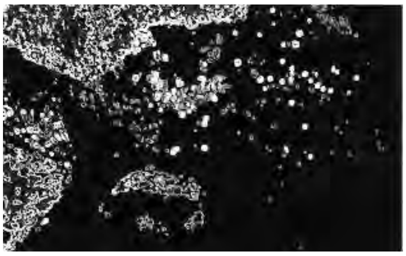


Figure 6
Parietal condensation droplets on a painted support, Lascaux.

of the alluvial water table. This site has been reinforced by the construction of a ring of walls and also has been covered over by a concrete slab.

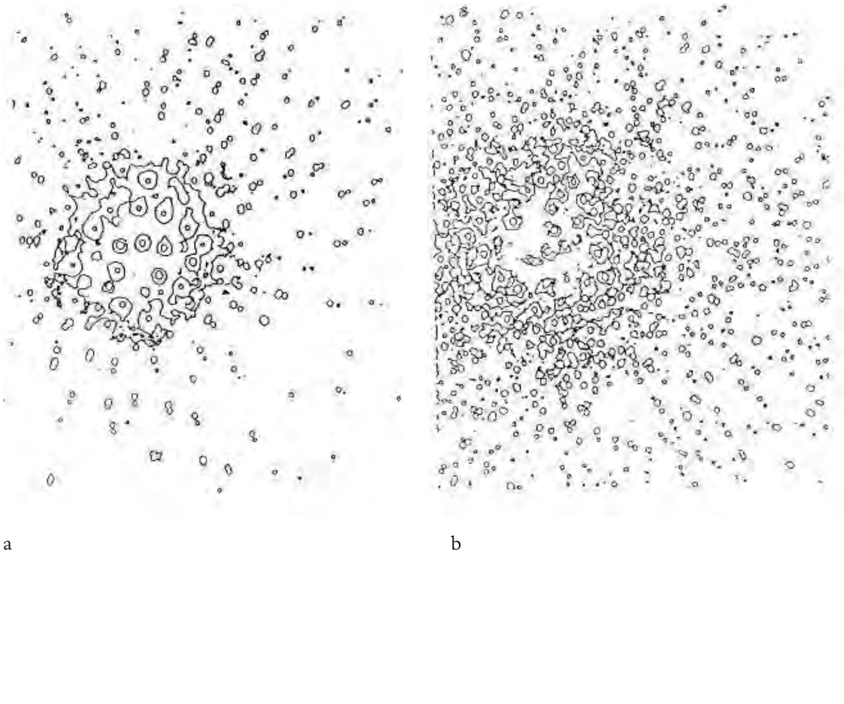
The surrounding archaeological excavation remains active for eight hours per day. Continuous recordings of the ground temperature and subterranean air and wall temperatures, as well as the air hygrometry, make it possible to calculate the imbalance between the water-vapor pressures in real terms. An air-extracting pump may be employed to dry the air, if necessary. In cases where condensation is developing (Fig. 4), it is possible to follow the moisture content of the wall surface (in this case, of a vault) by mapping the visual observations of the state of the site. Observations over time show increases and growth in the droplets that form on the recesses of the horizontal vault (Fig. 7a, b). These droplets lower the energy barrier necessary for the formation of a liquid-vapor interface. Small, separate droplets increase in size at the expense of the vapor, then merge; when they have reached their maximum size, they fall off and soak the ground, as well as structures and archaeological objects. The cycle of evaporation from the ground and condensation on the vault leads to destabilization of poorly adhered materials.

A Controlled Subterranean Environment: The Cave of Lascaux

Since its discovery in 1940, the cave of Lascaux has been subject to a number of adverse circumstances, making it a very complex model (Fig. 8a, b). Situated at a depth of 0–25 m below ground (Fig. 9), this cave highlights the problems of conserving original works of art and necessitates a definition of the ideal subterranean climate (Figs. 10–12). The restoration of the original atmosphere is one of the main aims of the conservation program (Vouvé et al. 1983).

From 1958 to 1963, a mechanical forced-air system was installed in the machine room for regulating the cave environment to account for the increasing number of tourists. The result was a system designed to adapt the subterranean climate of the cave to the visits.

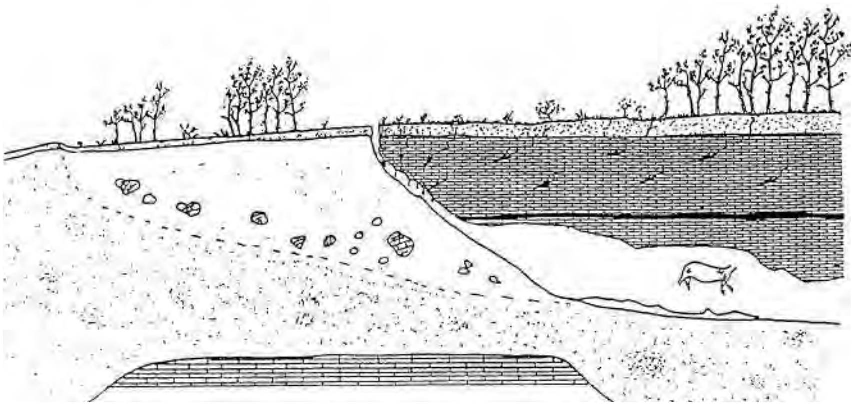
Figure 7a, b
Cartography of the evolution of the condensation droplets on the horizontal vault of an archaeological site shown (a) on 25 March 1992 and (b) on 28 March 1992.



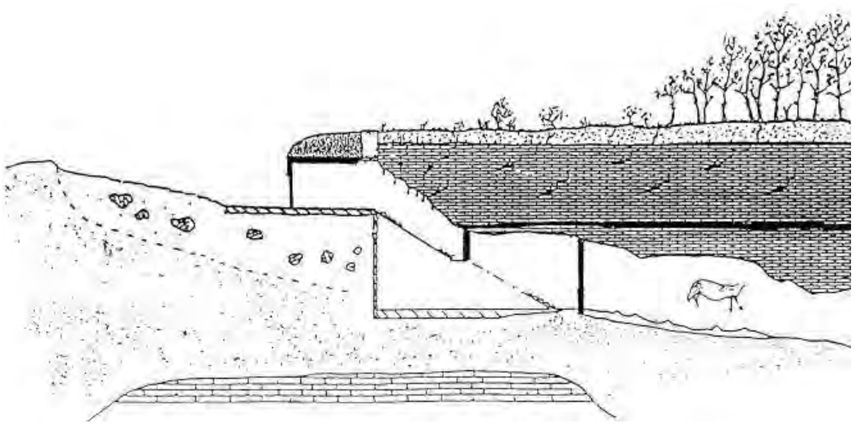
a

b

Figure 8a, b
State of the access of Lascaux (a) in 1940, the year of its discovery; and (b) in 1963.



a



b

Extensive scientific study preceded the installation of the regulating equipment (Malaurent, Vouvé, and Brunet 1992:319–32). The research monitored the following parameters (Fig. 9):

- Temperature of the air inside the cave at twenty-four specific points
- Temperature of the rock inside the cave at nineteen specific points
- Readings of the maximum and minimum external temperatures, and rainfall data from a meteorological station
- Assessment of the development of water from the phreatic water table intercepted by the entrance porch
- Assessment of the temperature at the intake and outlet vents of the primary cooling system
- Assessment of the temperature at the intake and outlet vents of the two secondary cooling systems
- Regulation of the output of the primary and secondary cooling systems
- Readings of air and water-vapor pressure taken with psychrometers from several strategic points within the cave
- Readings of CO_2 content in the enclosed spaces and pits

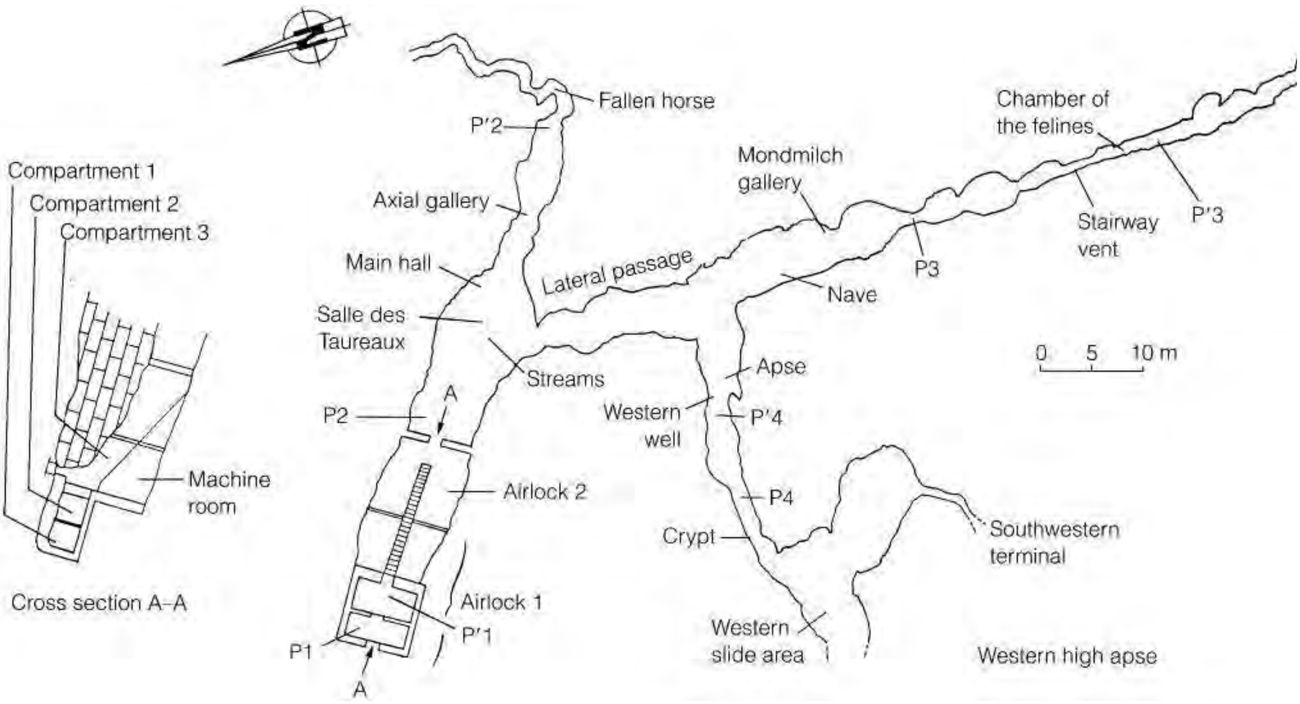


Figure 9
Map of Lascaux cave with main points where measurements were taken.

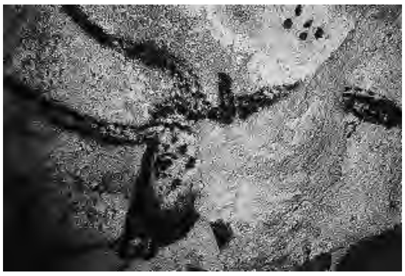


Figure 10
Painting in the Salle des Taureaux, Lascaux, showing an animal drawn on limestone and concretion.

- Visual assessment of condensation on sensitive surface areas inside the cave
- Visual assessment of all the decorated surfaces
- Photographic assessment of pinpointed trouble spots

The air-conditioning system has two closed circuits: circuit A (at a temperature of 5 °C), linked with the external cooling units; and circuit B (at 7 °C), which is internal. These two circuits are connected by exchanger D (Fig. 13). Exchangers C provide negative kilocalories (cold) from about June to December. Thus, controlling seasonal variations caused by the removal of part of the original screen, which acted as a natural exchange regulator between the Salle des Taureaux and the central branch of the cave, resulted in relatively good conservation conditions for the paintings (Fig. 9).

Monitoring of the rock in the Salle des Taureaux (chamber of the bulls) has demonstrated the need to control seasonal factors. Because of the slow progression of thermal waves in the ground during the winter period, the rock in this area is influenced by the air coming from more exposed areas, such as the machine room, which is closer to the exterior. Cooling air circulating from the cave's vault network to the top openings in the machine room produces water condensation (from one to several liters of water per day) on the radiators (the coldest points in the system). The cooled air, which is now drier, then returns to the decorated vault network via the bottom openings in the machine room (Fig. 13).

In June, the cave generally appears to be in a stable condition, and the temperature of the rock surface begins to fall naturally with the onset of winter. However, the premise is that the water-vapor level in the

Figure 11
"Chinese horse" drawn on cauliflower deposit.

Figure 12
Frieze of deer drawn on limestone.

machine room air is higher than in the Salle des Tauraux. In order to avoid any condensation on painted walls, the cooling system is turned on. This helps stabilize the water-vapor pressure of the air and prevents condensation on the walls (Fig. 14).

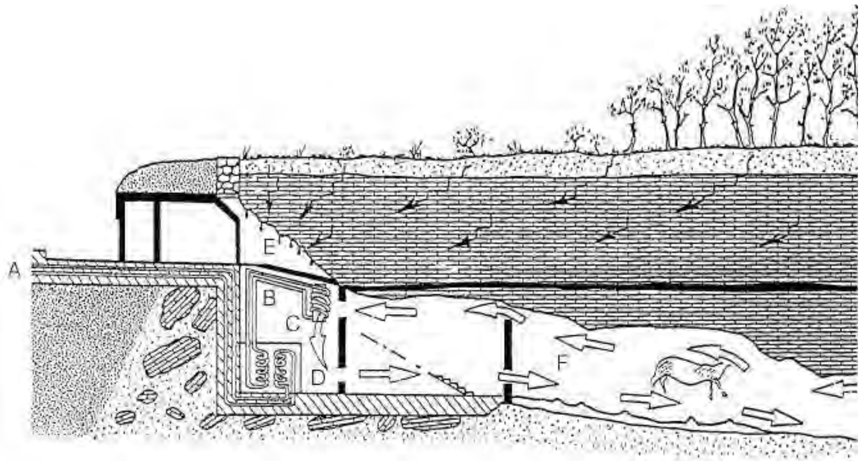


Figure 13
Lascaux, simplified diagram of the air circulation in the cave. The cross section shows the accelerated convection controlled by machinery between the Salle des Taureaux and the machine room. Scale drawing showing the dynamic of airflow in the rooms and corridors: A = primary cooling system; B = secondary cooling system; C = thermic exchangers; D = cylindrical thermal exchanger; E = infiltration water; F = air circulation by natural convection.

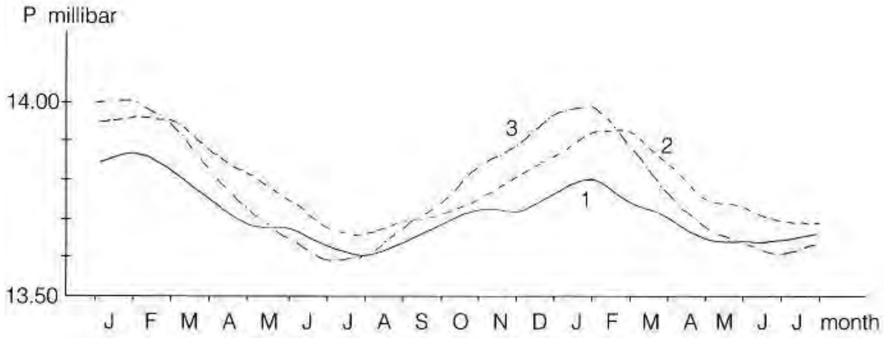


Figure 14
Diagram showing the pressure of water vapor expressed in millibars in the Salle des Taureaux: curve 1 = partial pressure of water vapor in the air; curve 2 = partial pressure of the counterbalancing water vapor of the surface of the rock on the left-hand wall; curve 3 = partial pressure of the counterbalancing water vapor of the rock on the vault. A comparison of curves 1 and 2 shows that there is no possibility of water vapor condensing, for example, on the rock near the drawing called "Unicorn."

Conclusions

Like any cave system, the Lascaux caves are a complex, living environment where different physical, chemical, and biological processes are constantly taking place and are subject, with a delayed effect, to external influences transmitted through rock, water, and air. The cave paintings are affected by the thermal, hydrous, chemical, and biochemical exchanges between rock and air.

Studies have revealed the relationship of this cave site to its environment; they have clearly shown that the equilibrium reestablished after all the changes the caves have undergone since their discovery in 1940 is of an extremely delicate nature.

The best possible conditions for the conservation of paintings have been achieved as a result of the smooth functioning and maintenance of the mechanical equipment. This is used to regulate the temperature of the caves through the operation of heat exchangers.

For Lascaux, as for other archaeological sites where wall paintings or drawings have finally been brought into a state of equilibrium with the environmental conditions, the authors agree with Mora, Mora, and Philippot (1977). These authors find that the best solution is to ensure conservation in situ by means of an overall air-conditioning system designed either to maintain the original conditions or to modify them very gradually, if and when necessary, under very close supervision.

Scientific conservation of cave sites depends largely on the ability to predict climatic and atmospheric changes, an ability that is grounded in knowledge of the changeable nature of the atmosphere. This understanding is essential in designing a conservation strategy that takes these parameters into account along with the need to obtain information concerning them as quickly as possible through the monitoring of both normal conditions and exceptional phenomena. Conservation professionals now have access to sophisticated equipment, such as reliable, battery-operated, high-performance telemeasuring units that, apart from being versatile, adapt to their environment and transmit information about it. Thus, it is now possible to control, organize, and influence most historic monuments at will, be they aboveground, half buried, or subterranean.

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Deposition of Atmospheric Particles within the Yungang Grottoes

Christos S. Christoforou, Lynn G. Salmon, and Glen R. Cass

Archaeological sites, especially those exposed to nature's elements, degrade with time. This is due to physical, chemical, or biological erosion. Air pollution, wind-borne dust, and weathering by the elements over time can be significant factors. One such site is the Yungang grottoes in China. These grottoes are a collection of more than twenty cave temples, hollowed out of a sandstone cliff at Yungang, near the industrial city of Datong in northern Shanxi province. The work at Yungang was initiated under the supervision of the monk Tan-yao in 460 C.E., supported by the patronage of the Northern Wei dynasty. The five earliest caves were excavated in memory of the ruling monarch and his four predecessors. A number of lesser caves and niches were excavated during the early part of the sixth century (Cox 1957; Sickman and Soper 1968; Knauer 1983).

Most of the larger caves are similar in architecture, with rectangular rooms 10–15 m on each side, excavated around a central pillar that stretches from the floor of the cave nearly to the ceiling. Usually, the pillar is carved into a monumental statue of the Buddha. There are examples, such as Cave 6, where the central column is sculpted in the form of a pagoda. The caves usually have two openings to the outside: an entrance at ground level, and a window higher up at about the third-floor level. The interior walls of the caves are adorned with many sculptures and carvings that depict scenes from the life of the Buddha. Many of these carvings are still polychromed.

In antiquity, a wooden temple building one room deep was added to the front of each cave, as can be seen today only in front of Caves 5 and 6. According to reports (Cox 1957), repairs to the caves were made during the eleventh and seventeenth centuries, but by the early twentieth century they had fallen into a state of neglect. In more recent years, repairs have been made to stabilize some of the sculptures, and the area around the grottoes has been turned into a park. During 1986, the caves were cleaned, and documentary photographs of the statues were taken. Today the Yungang grottoes are open to the public, and they receive hundreds of visitors daily.

Yungang is located in the middle of one of China's largest coal mining regions. Airborne particles are generated by the various processes at the mines. Trucks that carry the coal away from the mines travel on a highway located only a few hundred meters away from the entrance of the caves, and these trucks generate a considerable amount of airborne coal dust and road dust. Coal is also used for heating and cooking in the village of Yungang, as well as to fuel the trains that transport coal from the mines. Airborne particles also are generated by traffic on the unpaved dirt roads in the village of Yungang, located immediately adjacent to the grotto site. A seasonal source of dust is present, especially in the spring, when winds blow from the desert, carrying soil particles. As a result of all these factors, the grottoes suffer from a severe soiling problem.

During April 1991, the authors conducted an extensive air monitoring program at the Yungang grottoes. Some of the experiments performed over the period of 12 April to 1 May 1991 are as follows:

1. The mass concentration and chemical composition of airborne particles and some pollutant gases (SO_2, NO_2, NH_3, HNO_3, HCl) were measured both outdoors and inside Caves 6 and 9. These measurements help to define how much dust and smoke is present in the outdoor air, and what fraction of that material is found inside the caves. Cave 6 retains its traditional wooden temple front building, while Cave 9 is open directly to the outdoor environment. One purpose of examination of these two sites was to measure the protective effect, if any, provided by the temple structure in front of Cave 6.
2. The size distribution of the airborne particles was measured both outside and inside Caves 6 and 9. This particle-size information was needed to support the design calculations for airborne particle–control systems, because the efficiency of particle filtration equipment depends heavily on adaptation to particle size.
3. The particle deposition flux onto both horizontal and vertical surfaces was measured outside and inside Caves 6 and 9. This allowed deposition rates measured during the 1991 experiments to be compared to historically observed particle accumulation rates on the statues. It also quantified the actual problem that this work was intending to control.
4. The air exchange that transports outdoor airborne particles into the caves was measured, along with indoor-outdoor pressure differences and the cave wall-air temperature differences that cause this air exchange.

In addition, the staff at the Yungang grottoes operated air-sampling equipment and measured airflow into and out of Caves 6 and 9 during the months of July and October 1991 and January 1992. This extended experiment, when combined with the April experiments, permitted a full annual cycle of conditions at the grottoes to be examined.

Experimental Methods

Many of the experimental methods used at the Yungang grottoes were essentially the same as the procedures that the authors have developed for examination of particle deposition and soiling problems inside Southern California museums, under the sponsorship of the Getty Conservation Institute (Nazaroff et al. 1990; Nazaroff et al. 1992, 1993; Ligocki et al. 1993).

Sampling equipment was placed outside Cave 9, under the protective overhang of the cliff above, and inside both Caves 6 and 9, at locations shown in Figures 1 and 2. Horizontally and vertically oriented deposition plates for dust collection were placed both outside and inside the caves, as shown in these figures. Airborne particle-mass concentration was measured by collection on membrane filters, followed by chemical analysis for carbon particles, ionic species—including sulfates, nitrates, chlorides, and ammonium ion—and trace metals from which soil-dust mineralogy can be studied. Pollutant gases were measured by collection on chemically treated backup filters, located downstream of filters used for particle collection.

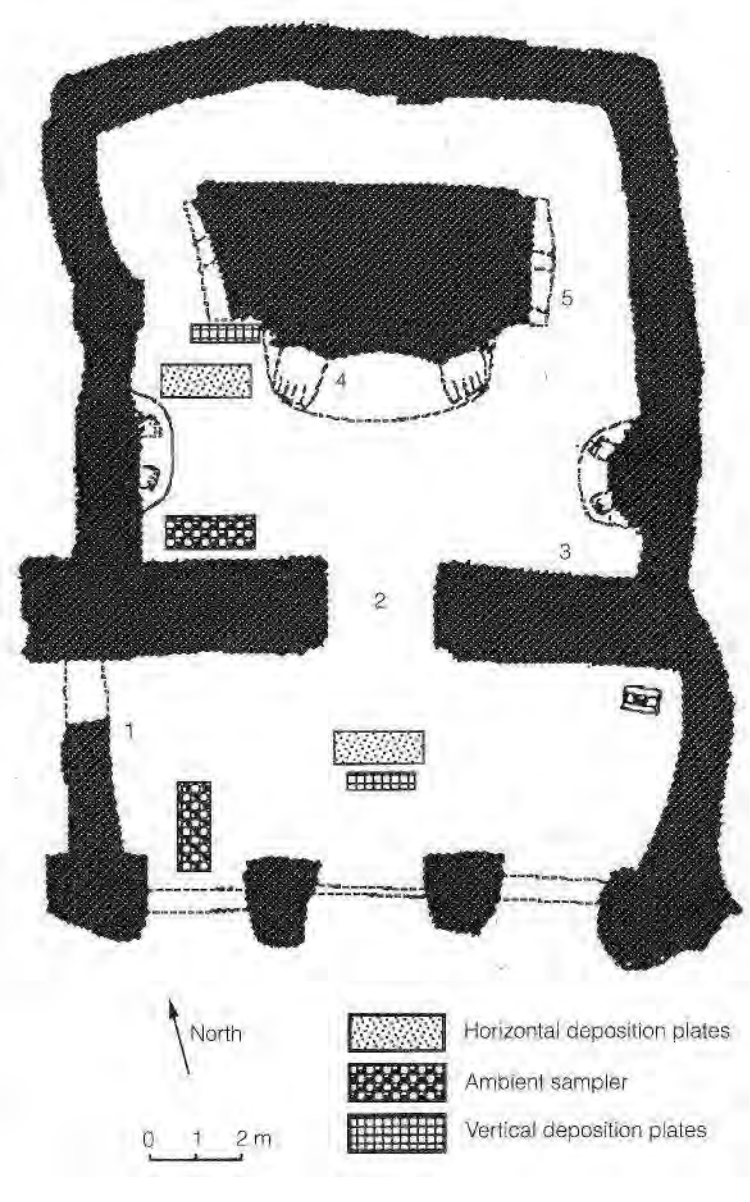
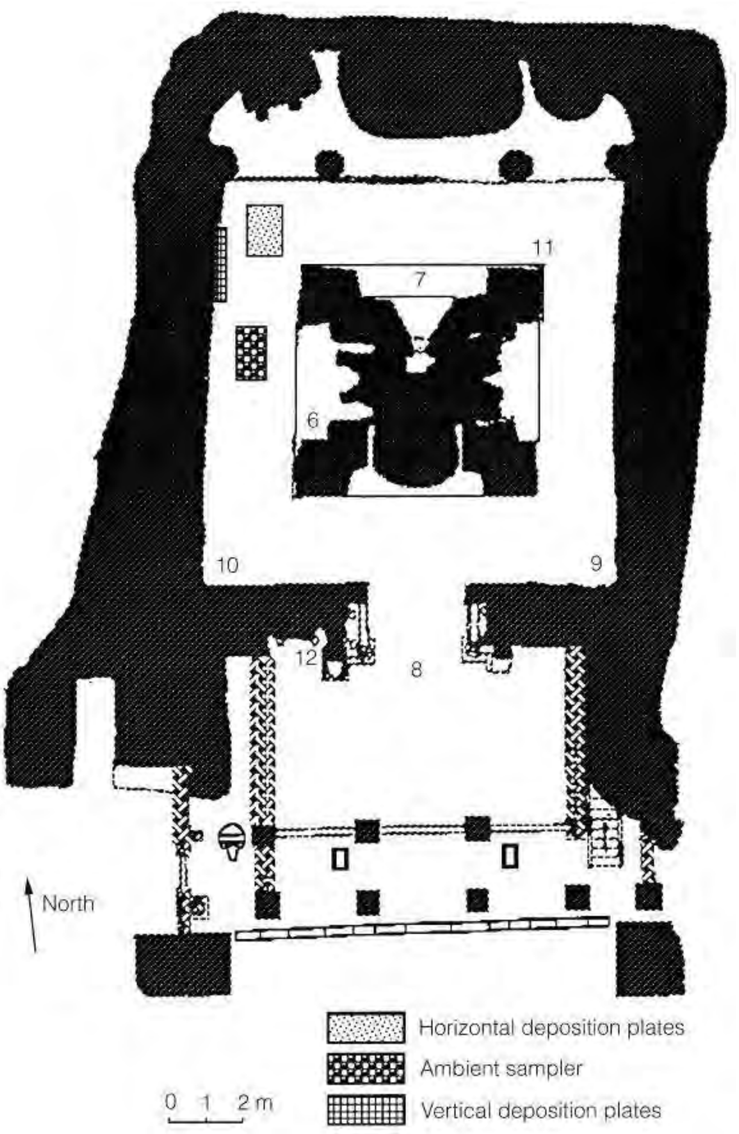


Figure 1
Location of ambient atmospheric particle samplers, deposition plates, and sites (numbered) at which historically accumulated particle deposits were measured in Cave 9 at the Yungang grottoes (from Christoforou, Salmon, and Cass 1994).

Figure 2
Location of ambient atmospheric particle samplers, deposition plates, and sites (numbered) at which historically accumulated particle deposits were measured in Cave 6 at the Yungang grottoes (from Christoforou, Salmon, and Cass 1994).



The size distribution of airborne particles was measured by computer-controlled, automated light microscope analysis of samples collected on membrane filters, while the size distribution of particles deposited on surfaces was measured by the same method applied to glass microscope slides that were used as deposition collectors in the caves. A complete description of experimental and analytical methods is given in the original technical reports on this work (Christoforou, Salmon, and Cass 1994; Salmon, Christoforou, and Cass 1994).

Airborne Particle Concentrations

The annual average concentration and chemical composition of outdoor airborne particles at Yungang is shown in Figures 3 and 4, from data contained in Salmon, Christoforou, and Cass (1994). The coarse particles examined in Figure 3 are large dust particles (diameter greater than 2.1 μm) that settle out of the atmosphere easily, while the fine particles (diameter less than 2.1 μm) examined in Figure 4 are the size of those in cigarette smoke and follow the air flow without depositing easily.

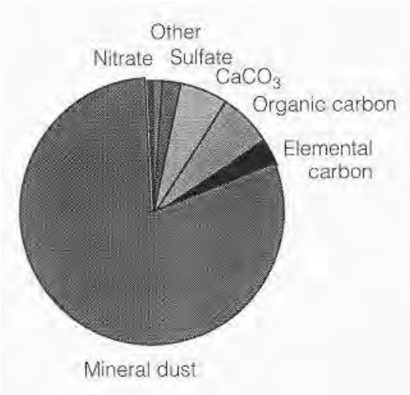


Figure 3
Chemical composition of coarse airborne particles (diameter > 2.1 μm) measured outdoors at the Yungang grottoes, 1991–92. The annual average coarse-particle concentration is 378 μg m^{-3}. Course particles are about 80% mineral dust plus about 10% carbon particles (e.g., coal).

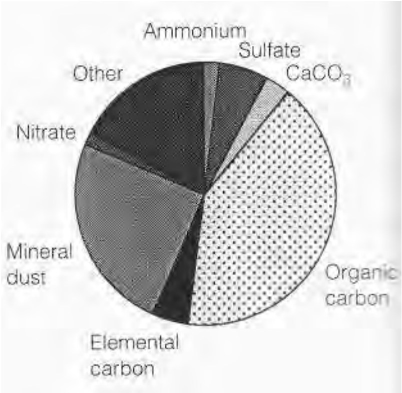


Figure 4
Chemical composition of fine airborne particles (diameter < 2.1 μm) measured outdoors at the Yungang grottoes, 1991–92. The annual average fine-particle concentration is 130 μg m^{-3}. Fine particles are about 46% carbon plus about 24% mineral dust.

Annual coarse-particle concentrations outdoors during 1991–92 averaged 378 μg m^{-3}, increasing to more than 1,200 μg m^{-3} during peak twenty-four-hour sampling periods. These coarse-particle concentrations are quite high, about six times higher than in the middle of the city of Los Angeles, California. The coarse particles consist largely of mineral dust, accounting for over 80% of the coarse-particle-mass concentration. Carbon-containing particles (organic compounds plus black elemental carbon) account for an additional 10% of coarse-particle mass.

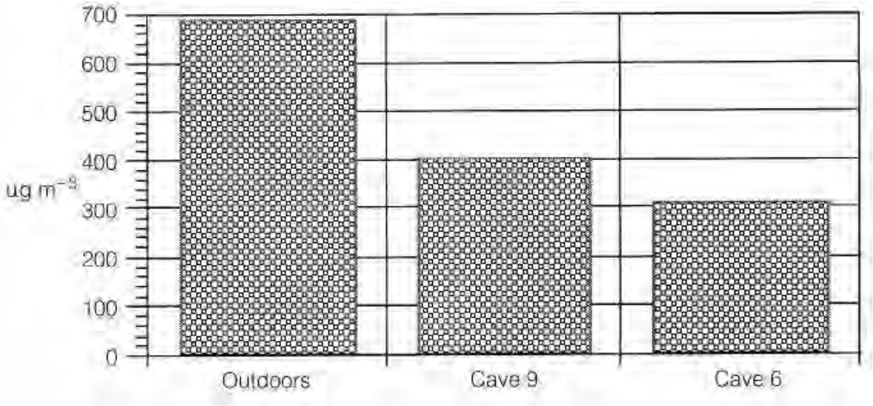
Airborne fine-particle concentrations outdoors averaged 130 μg m^{-3}. That is about four times higher than in the center of downtown Los Angeles, a location generally thought to be quite high in fine particles. These very small particles consist of carbon-containing particles (46%), followed in importance by mineral dust (crustal, 24%).

Figure 5 shows airborne particle concentrations during April 1991, when samples were taken outside and inside both Caves 6 and 9. Concentrations inside Cave 9 are lower than outside but higher than in Cave 6. Cave 9 receives air directly from outside because there is no wooden temple front building to provide particle removal or protection, as in the case of Cave 6. The concentrations inside Cave 9 are lower than outside, probably because of particle removal by deposition onto surfaces inside the cave, as there is no other mechanism for particle removal at this cave.

Dust Deposits in the Caves

The rate of accumulation of deposited particles on upward-facing surfaces was measured over a one-year period (Christoforou, Salmon, and Cass 1994). The annual average mass deposition rate to horizontal surfaces was 13.4 μg m^{-2} s^{-1} outside and 5.2 μg m^{-2} s^{-1} inside Cave 6, as shown in Table 1. During April 1991, particle deposition measurements were made in Cave 9 and were found to be halfway between the mass flux measured outdoors and that measured in Cave 6. Historical accumulations of dust

Figure 5
Airborne particle concentrations measured outdoors, inside Cave 9, and inside Cave 6 during April 1991, showing the extent of protection provided by the present temple building in front of Cave 6, as compared to Cave 9, which lacks a structure.



were removed from measured areas in Caves 6 and 9 at the numbered locations shown in Figures 1 and 2, which are known to have been cleaned in 1986 (Christoforou, Salmon, and Cass 1994). Indoor deposit depths that accumulated on horizontal surfaces over that five-year period (1986–91) range from 0.1 to 0.8 cm, with mass accumulations up to 5 kg m^{-2}, as shown in Table 2. In Table 3, it is seen that the particle deposition rates measured during the 1991–92 experiments, if extrapolated to a five-year estimate, are within about a factor of two of the historically observed rate of particle accumulation. This suggests that our data provide a reasonable basis for testing the likely long-term effect of various particle deposition–control proposals.

Dust deposits removed from surfaces in the caves at locations shown in Figures 1 and 2 have been examined by optical microscopy and have been analyzed chemically by neutron activation analysis, by low-temperature ashing, and by X-ray diffraction (XRD). Dust deposits analyzed by optical microscopy show that the deposits consist of quartz (typically 14–44%) and feldspar (typically 14–30%), clay and other polycrystalline materials (typically 10–22%), and unburned coal dust (15–40%), plus a few

Table 1 Mass flux of particles deposited onto horizontal surfaces at Yungang, measured on glass deposition plates (from Christoforou, Salmon, and Cass 1994)

Location	Date	Mass flux (mg m^{-2} s^{-1})
Outdoors	April 1991	21.5
Cave 9	April 1991	13.4
Cave 6	April 1991	4.5
Outdoors	July 1991	12.7
Cave 6	July 1991	5.4
Outdoors	October 1991	7.2
Cave 6	October 1991	5.8
Outdoors	January 1992	12.3
Cave 6	January 1992	5.1
Outdoors	Annual average	13.4
Cave 6	Annual average	5.2

Table 2 Measurements of historical particle deposits accumulated on the sculptures in Caves 6 and 9 over the period of 1986–91. Measurements that were made at the locations in Caves 6 and 9 are shown in Figures 1 and 2 (from Christoforou, Salmon, and Cass 1994)

Site	Location	Depth (cm)	Mass (g m^{-2})
Outdoors	1	0.76	6658
Cave 9	2	0.25	2695
Cave 9	4	0.13	572
Cave 9	5	0.80	4981
Cave 6	6	0.13	201
Cave 6	7	0.06	113
Cave 6	9	0.50	156
Cave 6	10	0.40	171
Cave 6	11	0.50	298
Cave 6	12	0.10	370

Table 3 Comparison of particle mass accumulated during the period of 1986–91 compared to that of the five-year estimate from the 1991–92 deposition experiments

Location	1986–1991 Actual, g m^{-2}	Five-year estimate from glass plate samples, g m^{-2}
Inside Cave 6	113–370	716
Inside Cave 9	572–4981	2113
Under cliff overhang in front of Cave 9	6658	3390

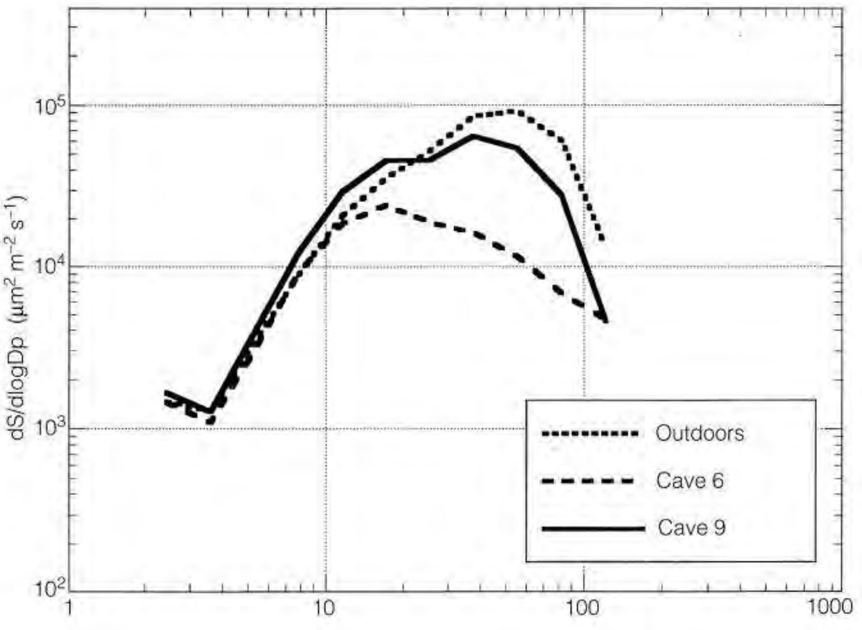
percent calcite. Low-temperature ashing likewise suggests that the dust deposits contain 18–32% coal dust. That the deposits are composed of a mixture of soil dust and coal dust is quite consistent with the nature of the pollution sources nearest to the caves.

The rate of surface area coverage by coarse particles on horizontal surfaces inside the caves is very rapid (Fig. 6). More than 0.2% of the horizontal surface area in Cave 6 is covered by newly deposited particles in less than two hours. This means that a human observer looking at a new sheet of white paper placed in the caves could detect visually that the paper was becoming soiled within a matter of hours (Hancock, Esmen, and Furber 1976). Fortunately, the particles that produce this soiling problem are rather large (as shown in Fig. 6), in the size range of 10 to 100 μm in diameter. Particles of that size are relatively easy to remove by filtration of the air entering the caves.

Conclusions

Airborne particle concentrations and deposition rates have been measured both inside and outside the Buddhist cave temples at Yungang. The outdoor particle concentrations were very high. Total particle concentrations averaged 508 μg m^{-3} over the year studied (1991–92), with 378 μg

Figure 6
Rate at which a horizontal surface at Yungang is covered by deposited particles as a function of particle diameter.



m^{-3} of that particle concentration present as coarse particles (diameter greater than 2.1 µm), and 130 µg m^{-3} of that particle concentration present as fine particles (smaller than 2.1 µm particle diameter).

Chemical analysis has shown that the airborne particles consist mostly of mineral dust (24% and 80% for fine and coarse particles, respectively) and carbon particles (46% and 10% for fine and coarse particles, respectively).

The deposition rate of coarse particles onto upward-facing horizontal surfaces also was measured. At the deposition coverage rate of 2.9×10^5 µm^2 m^{-2} s^{-1}, observed during the spring of 1991 within Cave 9, horizontal surfaces would reach 0.2% coverage—the minimum percentage for detectable soiling (Hancock, Esmen, and Furber 1976)—in about 6.9×10^3 s or 1.9 h (on average). This example is completely consistent with the authors' observations that the glass plates and millipore filters used as deposition collectors in these experiments were noticeably dirty at the end of a day. At such deposition rates, complete coverage of the horizontal surfaces in the caves by a monolayer of deposited particles would occur within 1.3 months. Over a period of six years, deposits as deep as 0.8 cm and weighing as much as 5 kg m^{-2} have been measured at sites known to have been cleaned in 1986.

Clearly, airborne particle concentrations and particle deposition rates are so high at present that, by continuously covering the statues with a layer of abrasive and dark-colored dust, they would defeat any attempt to restore the caves. Fortunately, the surface area coverage rate is dominated by particles between 10 µm and 100 µm in diameter, which can be filtered out of the air entering the caves fairly easily. In a subsequent chapter herein, the air-quality and particle-deposition data reported here are used to evaluate the likely effect of alternative approaches to control of the particle deposition problem at the Yungang grottoes (see Christoforou et al., herein).

Acknowledgments

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Control of Particle Deposition within the Yungang Grottoes

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The Yungang Grottoes, located near Datong, China, consist of more than twenty cave temples that contain dozens of monumental Buddhist statues and more than fifty thousand smaller sculptures. The sculptures within the caves are soiled at a rapid rate by the deposition of airborne particles. During April and early May 1991, experiments were conducted at Yungang to measure the nature of this soiling problem. The purpose of the experiments was to collect data necessary for the selection of an approach that would greatly reduce the soiling rate inside the caves.

The results of those experiments, reported in the technical literature (Christoforou, Salmon, and Cass 1994; Salmon, Christoforou, and Cass 1994) and summarized by Christoforou, Salmon, and Cass herein, show that the outdoor airborne particle concentrations at Yungang are very high, averaging 508 $\mu g\ m^{-3}$ over an annual period (1991–92). Deposition of particles, typically ranging in size from 10 to 100 μm in diameter, occurs on horizontal surfaces within the caves largely due to gravitational sedimentation. The result is that the horizontally oriented surfaces of the sculptures within the grottoes can become noticeably soiled within a matter of hours and can become completely covered by the first monolayer of deposited dust within 1.3 months. Over a period of six years, deposit thicknesses as deep as 0.8 cm and weighing as much as 5 $kg\ m^{-2}$ have been measured on the statuary in the caves (see Christoforou, Salmon, and Cass herein).

Measurements of the chemical composition of the airborne particles and of the dust deposits on surfaces in the caves show that they consist of mineral matter (e.g., soil dust) and carbon particles (e.g., unburned coal dust) (Salmon, Christoforou, and Cass 1994; Christoforou, Salmon, and Cass herein). This is consistent with observations of the major dust generation activities in the vicinity of Yungang, which include emissions from large coal mines in the region; coal dust and road dust from trucks carrying coal (especially along a road located approximately 300 m to the south of the grottoes); dust from travel on unpaved roads in the village

of Yungang, adjacent to the grottoes; dust generated by visitors and maintenance activities on the unpaved terrace immediately in front of the caves; soil dust generated by wind storms from the Gobi Desert, and smoke from local coal combustion.

The purpose of this article is to examine alternative approaches to the control of the particle deposition problem within the Yungang grottoes. Two general approaches are possible: (1) control of particle concentrations in the outdoor air through reduction of particle generation at the aforementioned sources, and (2) removal of particles from the air entering the caves by filtration or similar technical means. Each of these alternatives is discussed in quantitative terms, based both on field experiments conducted at Yungang and on computer-based models of the particle deposition processes within the caves.

Control of Outdoor Pollutant Concentrations

A map of the immediate vicinity of the Yungang grottoes is shown in Figure 1. The cliff face into which the cave temples are excavated appears as an east-west line along the middle of the map. There is a park within the walls of the grotto grounds immediately to the south of the cliff face. The small village of Yungang lies directly to the south of the park in front of the caves. A major highway, carrying thousands of coal trucks daily, is located on the south and west sides of the village. A river runs past the grottoes site to the south and west of the coal-hauling highway. Just south and west of the river is a railroad line for coal-fired locomotives. Coal mines are sited at the periphery of the map, as well as up and down the river valley beyond the boundaries of what is shown in Figure 1.

Over a two-day period in April 1991, the authors measured the spatial distribution of the deposition of airborne particles at the center of a series of 0.5×0.5 km map sections laid out over the 2×2 km area surrounding the caves shown in Figure 1 (Salmon et al. 1995). Extra samples were collected within the village of Yungang and along the terrace in front of the caves. Measurements were made on glass deposition plates, and those results are shown in Figure 1. The highest deposition rates (about 60 $\mu g\ m^{-2}\ s^{-1}$) occur in the center of the map, within the village of Yungang and along the coal-hauling highway. Lower particle fluxes generally occur at the edges of the area mapped. This means that the sources that generate much of the airborne particulate matter are located within the high-flux area, principally along the coal-hauling highway and inside the village of Yungang. The caves are located between the cleaner countryside and the very dusty area along the highway and the main street of the village. As a result, the particle deposition flux at the front of the caves is lower than that along the coal-hauling highway or in the village, but is higher than that in the surrounding countryside.

Because the area that seems to contain this high source of particles is fairly small, it may be practical to reduce much of the local particle generation by the following simple means: (1) redirecting the coal-truck traffic to roads located far from the grottoes or, alternatively, covering the loaded coal trucks so that coal does not fall off to be crushed and driven

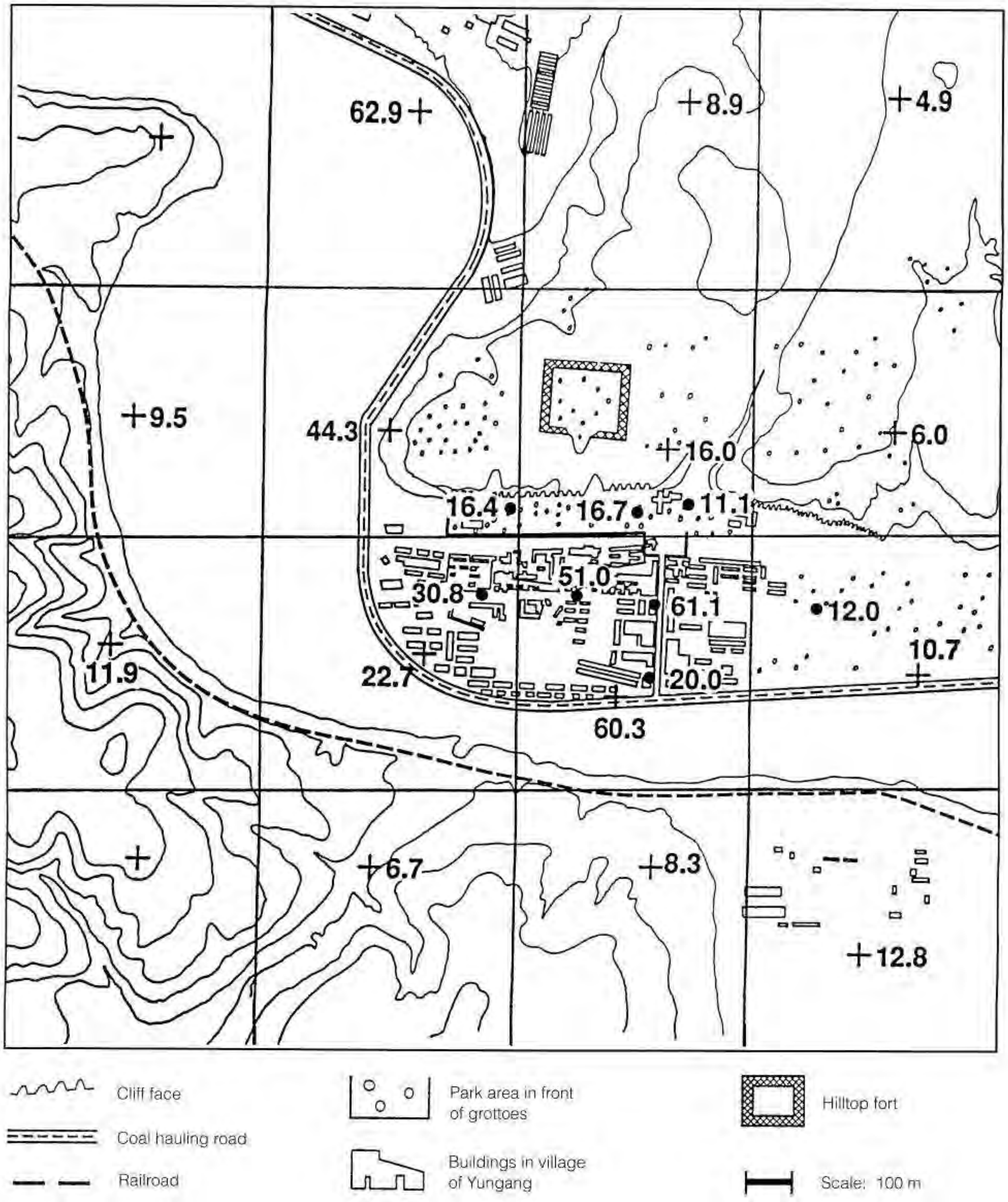

Figure 1

Map of the 2 × 2 km area surrounding the Yungang grottoes that was studied to determine the spatial distribution of the local particle deposition problem. Values shown at the experimental sites marked by + or · are airborne particle deposition rates in $\mu g\ m^{-2}\ s^{-1}$ measured over the period of 19–21 April 1991 (from Salmon et al. 1995).

into the air by trucks that follow; and (2) paving the few streets in the village of Yungang so that vehicle traffic produces much less dust there.

The authors have had occasion to observe that the city of Xian employs an excellent additional measure for dust suppression: a tank truck uses water to spray down the roads in the morning. This may, at first, seem impractical at Yungang, given the obvious general shortage of water in the area. But it should be seriously considered, as it is a measure that

the grottoes staff could undertake on their own initiative with little required assistance or cooperation from others. The sections of road to be washed (i.e., the section of the highway on the map of Figure 1, plus the village roads) are very short. The grottoes do have their own water source, but that water may not have to be used. There is no reason to wash the roads with high-quality water when a tank truck can fill up at the river (as long as the river is not dry). If necessary, a well could be drilled to increase the supply of locally available water.

A further source of possible dust creation is foot traffic and sweeping activity that occurs on the dirt terrace directly in front of the caves. Much of the dust deposited within the caves has a mineral composition similar to that of local soil dust. It is not easy to tell how much of this dust comes from the terrace in front of the caves and how much comes from the village. The Yungang grottoes staff has reported that there is a plan to pave the dirt area in front of the caves with stepping-stones, as a means of reducing dust generation at that site.

If localized particle generation from the coal-hauling highway, from the village, and from the dirt area just in front of the caves could be suppressed, particle deposition rates would begin to approach those in the areas of Figure 1 that are more distant from the caves. A reduction in particle deposition rates from about 16 $\mu g\ m^{-2}\ s^{-1}$ at present at the entrance to the caves down to perhaps 10 $\mu g\ m^{-2}\ s^{-1}$ in the future on days with conditions similar to those measured and shown in Figure 1 may be a reasonable goal. That would reduce particle deposition at the caves by about 38%. The reduction would not be larger because the regional background deposition rate all over the countryside—due to regionwide dust sources that include the coal mines, more distant road traffic, and other villages—is fairly high, even at sites distant from local dust sources that can be controlled, such as those near the village of Yungang. Thus, the use of local dust suppression methods at Yungang does not provide a complete solution to the particle deposition problem, but it helps. It may make an important contribution to an overall control program.

Removal of Particles from Air Entering the Grottoes

Two options exist for removing particles from the air that enters the grottoes. First, a mechanical air-filtration system, powered by an electrical fan motor, could be used. In antiquity, the entrance to each of the caves was sheltered by a wooden temple front building that was one room deep and extended several stories up the face of the cliff. Two of these structures still exist today. A mechanical air-filtration system could be concealed within the upper stories of an existing or reconstructed wooden temple front building. Many mechanical air-filtration systems are maintained in Beijing at present, only about 265 km to the west of Yungang; similar systems could be maintained at Yungang in the not-too-distant future. The second option would be a passive particle-filtration system that could be designed to make use of the natural convection-driven air circulation within the caves to remove particles as air passes through filter material. This filter material would replace the paper that originally covered the

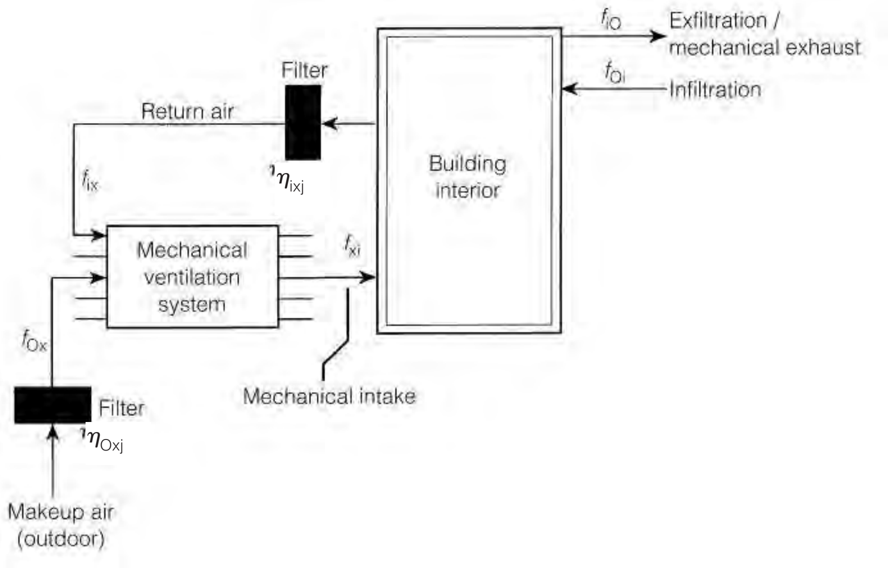

Figure 2
Schematic representation of the mechanical air-filtration system for a building. The symbols *f* and η indicate airflow rates and filter efficiencies, respectively (from Nazaroff et al. 1993).

numerous windows that exist within the door panels of a traditional Chinese temple structure.

Installation of a mechanical air-filtration system

Figure 2 shows a diagram of a standard mechanical air-filtration system for a building. Outdoor makeup air containing airborne particles is fed to the ventilation system through a particle filter and is then introduced into the building (in this case a cave) interior. Previously filtered recirculated air is withdrawn from the building interior, filtered again, and then sent back to the building. This repeated filtration of the recirculated indoor air means that the removal efficiency of the whole system—defined as the percentage of the particles originally contained in air entering the building that are subsequently collected by the air-filtration system—is greater than it would be if the air made only one pass through the filters as it enters the building. A certain amount of infiltration air usually leaks, unfiltered, into the building through cracks or when doors are opened and closed.

A filtration system for Cave 6 at Yungang, for example, could be built by placing a mechanical fan, ductwork, and filters in a hidden, unused area of the upper stories of the wooden building that stands in front of that grotto. Such a system can be operated using many possible combinations of filters, outdoor makeup airflow rates, recirculated indoor airflow rates, and untreated outdoor air infiltration. The likely effects of different designs were explored. First, a computer model of the particle deposition process in Cave 6 was built as it would exist both with and without a wooden building in front, based on the calculation approach previously described by Nazaroff and Cass (1989) and Nazaroff, Salmon, and Cass (1990). Next, several alternative particle-filtration system designs were considered. A schematic diagram showing one possible relationship between equipment location and airflow pathways for such a system within a

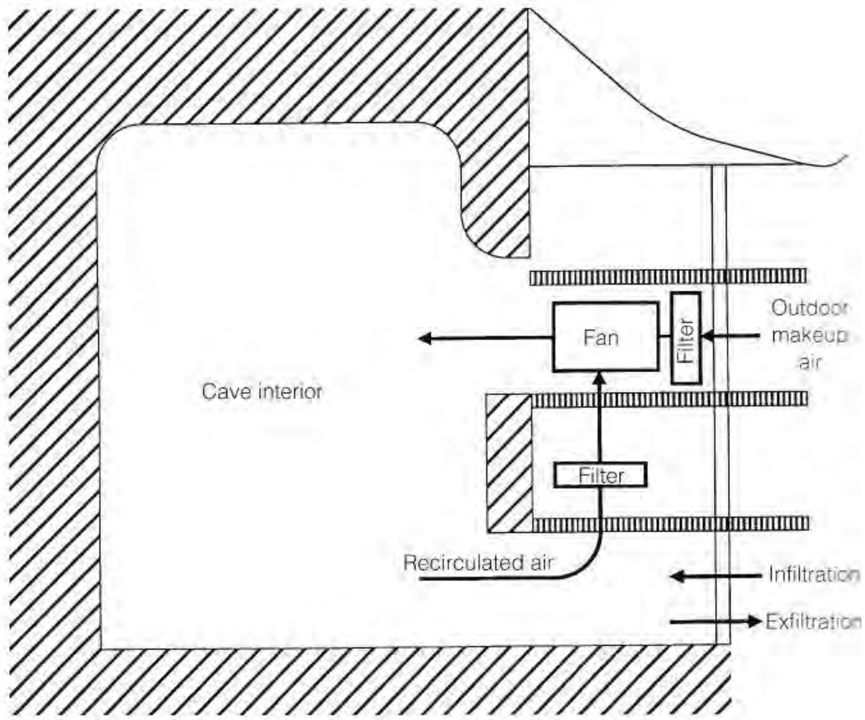

Figure 3
Schematic diagram showing one possible relationship between equipment location and airflow for a mechanical air-filtration system concealed within the upper stories of a structure that shelters the front of a cave at Yungang.

Buddhist cave temple front structure is given in Figure 3. Finally, the change in particle deposition rates onto horizontal surfaces were calculated for several different ventilation system designs.

To begin this study, a base case condition was established at Cave 6 as it would exist if there were no temple building in front of the cave. This was an important case to consider because most of the other grottoes at Yungang lack a wooden building at present. The computer simulation began with measured outdoor particle concentrations and particle sizes observed on 15–16 April 1991, and then followed those particles as they entered the cave with the measured airflow. Under uncontrolled base case conditions, particle mass amounting to 262 mg m^{-2} d^{-1} was calculated to deposit on horizontal surfaces, as seen in line 1 of Table 1. In the presence of the existing wooden building in front of Cave 6, the flow of untreated outdoor air into the grotto is reduced from what it would be without the wooden building. In a simulation of the historical case at Cave 6 (which includes the effect of the existing wooden shelter in front of that cave), the particle flux to horizontal surfaces was equal to 53% of that for a cave with a completely unsheltered entrance (see line 2 in Table 1). The calculated particle deposition rate to horizontal surfaces in this second case compared closely with the measured particle deposition for the days studied, as seen in Figure 4.

Mechanical air-filtration systems in commercial buildings typically employ about a 1:3 ratio between filtered outdoor makeup air and recirculated, refiltered indoor air (Fig. 2). The effect of a standard ventilation system such as this can be approximated by setting the total airflow through such a system at 317 m^3 min^{-1} (identical to the natural airflow that would exist without a wooden building in front of Cave 6), with 89 m^3 min^{-1} of

Table 1 Effect of alternative mechanical filtration system designs on reducing the particle mass flux to horizontal surfaces in Cave 6 at the Yungang grottoes

	Untreated outdoor infiltration air (m^3 min^{-1})	Filtered outdoor makeup air (m^3 min^{-1})	Filtered indoor recirculated air (m^3 min^{-1})	Filter type	Mass deposition to horizontal surfaces (mg m^{-2} day^{-1})	Percent remaining relative to base case	Time to 100% coverage by particles (years)
Base case							
(1) Temple front removed	317	—	—	—	262	—	0.28
(2) Historical case with wooden building	99	—	—	—	139	53	0.47
Mechanical ventilation with low-efficiency filters (F_{B1})							
(3) Standard system	10	89	267	FB1	92	35	0.75
(4) Reduced makeup air	10	22	334	FB1	37	14	1.8
(5) Standard system with zero infiltration	0.0	89	267	FB1	82	31	0.83
(6) Reduced makeup air with zero infiltration	0.0	22	334	FB1	24	9.2	2.6
Mechanical ventilation with loaded low-efficiency filters (F_{A3})							
(7) Standard system	10	89	267	FA3	12	4.6	5.7
(8) Reduced makeup air	10	22	334	FA3	9.9	3.8	7.2
(9) Standard system with zero infiltration	0.0	89	267	FA3	3.8	1.4	15
(10) Reduced makeup air with zero infiltration	0.0	22	334	FA3	1.5	0.6	36
Mechanical ventilation with high-efficiency filters							
(11) Standard system	10	89	267	88–99%	9.9	3.8	7.5
(12) Reduced makeup air	10	22	334	88–99%	9.4	3.6	8.0
(13) Standard system with zero infiltration	0.0	89	267	88–99%	1.5	0.6	42
(14) Reduced makeup air with zero infiltration	0.0	22	334	88–99%	0.93	0.4	72

Values shown are averages of model predictions over the two-day period of 15–16 April 1991, for which data are available to drive the deposition model. Deposition rates under annual average conditions are about four times higher than under 15–16 April 1991 conditions; deposition fluxes shown above should be scaled upward proportionately and the times to reach 100% coverage by particles should be divided by a factor of 4 when considering time periods that approach a year or longer.

outdoor makeup air and 267 m^3 min^{-1} of recirculated indoor air. The infiltration of untreated air is set at 10 m^3 min^{-1} (approximately 10% of the makeup airflow). In reality, this infiltration air will depend on how airtight the building is. The sum of outdoor makeup-air supply plus infiltration-air supply is identical to the 99 m^3 min^{-1} outdoor air exchange rate observed historically in the presence of the existing wooden building in front of Cave 6, which is important from the point of view of water vapor removal. A separate study of the water vapor balance in Cave 6 is still needed to determine whether or not that historically observed air exchange rate is appropriate; the outdoor airflow could easily be increased if necessary. Initially, low-efficiency filters will be tried that have a single-pass particle removal efficiency of 14–34%, based on measurements made in a particular Southern California museum filtration system (see filter performance curve F_{B1} in Fig. 5, from Nazaroff et al. 1993). The result of such a system would be the reduction of particle deposition to 92 mg m^{-2}

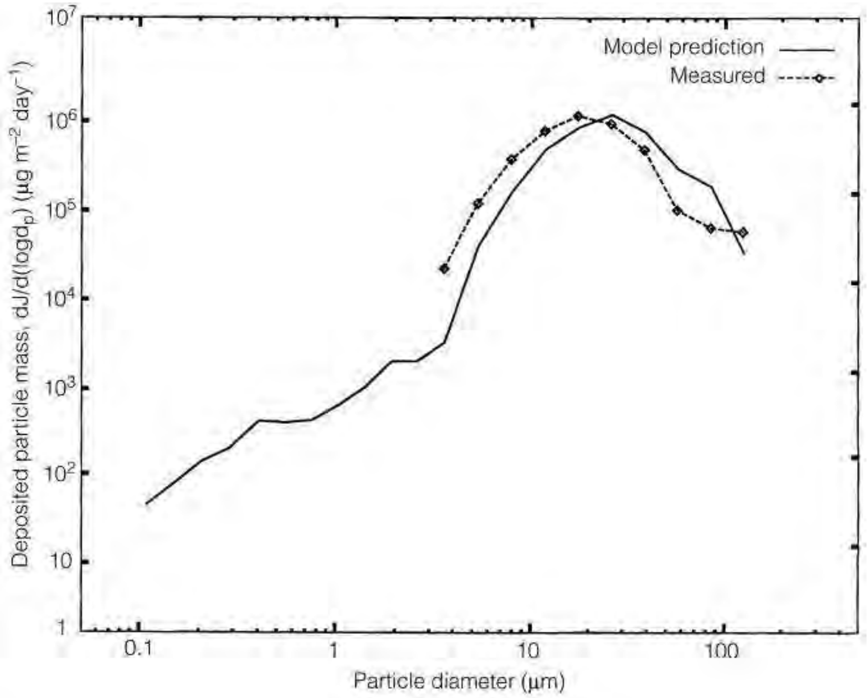

Figure 4
Measured particle mass deposition rates onto horizontal surfaces as a function of particle size inside Cave 6 at Yungang, compared with model predictions of particle deposition rates based on outdoor particle concentration, particle size distribution, and airflow through the caves, observed on 15–16 April 1991. This is the base case model-verification-result that corresponds to line 2 of Table 1.

d^{-1}, or to 35% of the uncontrolled case, as seen in line 3 of Table 1. These filters were studied purely to illustrate the effect of changing the filtration efficiency. No recommendation of a particular filter manufacturer is intended at this point; that decision should be made later.

Further reduction in particle deposition can be attained by reducing the outdoor makeup air from 89 m^3 min^{-1} down to 22 m^3 min^{-1}, while increasing the return airflow, thus bringing fewer new particles into the cave. The result of this change is shown on line 4 of Table 1. Particle deposition would be reduced to 37 mg m^{-2} d^{-1}, or to 14% of the uncontrolled case. Though particle levels would be reduced, one must be careful

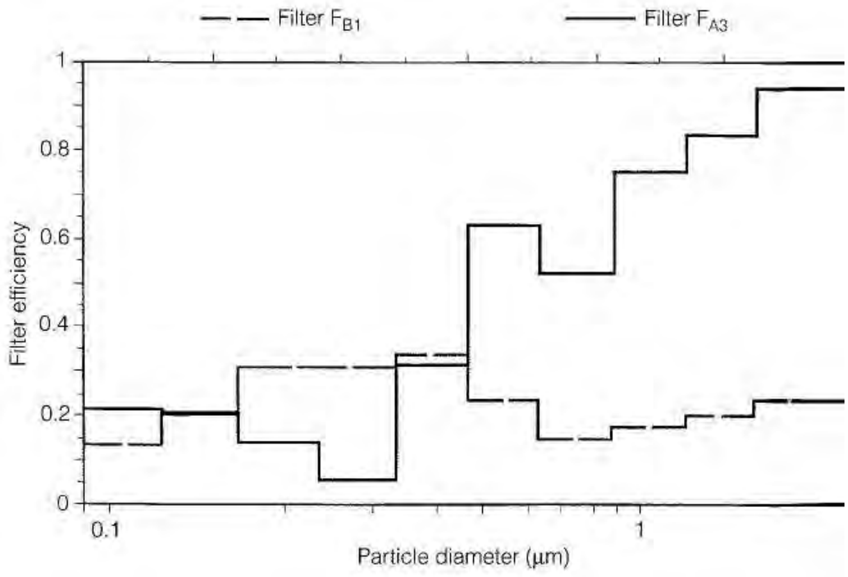

Figure 5
Filtration efficiency of particle filters as a function of particle size. The results are based on 21 hours and 4.5 hours of data for filters F_{A3} and F_{B1}, respectively. The corresponding operating flow velocities across the filter faces are 0.44 and 1.7 m s^{-1}. Filter media: Filter F_{A3} is Servodyne type SR-P1L; filter F_{B1} is Servodyne type Mark 80 (from Nazaroff et al. 1993).

to determine that the reduced air exchange rate does not lead to water vapor buildup in the cave.

No matter how good the filters are, the performance of the mechanical filtration system will be limited by the amount of untreated infiltration air that leaks into the building. The above two control cases have been rerun with zero untreated infiltration air, and the results are shown on lines 5 and 6 of Table 1. With the higher filtered outdoor makeup air supply, but no infiltration (line 5 of Table 1), particle mass deposition drops to 31% of the base case; with no infiltration air plus reduced makeup air, the particle deposition flux drops to 9.2% of the base case.

Further improvements can be made to the filtration system by using more efficient filters. One air-pass through filter F_{A3} (Fig. 5) removes about 96% of the very coarse dust particles that are causing much of the deposition problem in the caves. Filter F_{A3} has been used long enough that a "filter cake" of deposited particles has accumulated on its surface, making it harder for new particles to pass through the filter uncollected. This situation may be referred to as having a low-efficiency filter that is "loaded" with previously collected particles. The calculations performed in lines 3–6 of Table 1 are repeated for the case with the higher filtration efficiency of filter F_{A3}. Results are shown in Table 1, lines 7–10. The cases in lines 7 and 8 of Table 1 approach a situation in which about 4% of the particles in the outdoor air still remain, in spite of repeated passes through filters that are 96% effective per pass at removing coarse particles. This is occurring because unfiltered infiltration air is still entering. The purpose of the two cases on lines 9 and 10 of Table 1 is to illustrate the importance of eliminating untreated infiltration air. It may not be practical to completely eliminate infiltration, but it is important to try to do so. Relatively tight wood-frame buildings are constructed in the United States, so this requirement can even be met using traditional materials, if the structure is carefully designed.

A sequence of high-efficiency filters can be placed in the mechanical ventilation system to achieve 88% collection of fine particles and 95% (recirculated air line) to 99% (makeup air line) collection of coarse dust per pass. Such filters would cost more to operate because the pressure drop through the filters is higher, necessitating more power, a bigger fan, and more expensive filter material. In lines 11–14 of Table 1, the previous calculations are repeated for the case of the high-efficiency filters. The principal difference with the high-efficiency filters is that they reduce fine particle concentrations and thus will slow the rate of deposition onto the ceiling and vertical surfaces. The buildup of particles on vertical surfaces is already much slower than on horizontal surfaces. Before one can decide on the merits of the higher efficiency filters, it is important to know whether or not the horizontal surfaces of the statues (e.g., shoulders, tops of heads) will be cleaned separately and more frequently than the vertical surfaces (e.g., the chests of statues). If all surfaces are to be cleaned at the same time, then the horizontal surfaces will become dirty first and will trigger a round of cleaning regardless of whether filter F_{A3} or the more expensive high-efficiency filters are used. However, if one wants to clean

the vertical surfaces as infrequently as possible, the high-efficiency filters will make this possible.

Passive filtration systems

Given the large airflows through the caves caused by natural convection, the question arose: Is it possible to filter the particles out of the air entering the caves without using a mechanical fan to move the air? The authors approached this question by first building a computer-based model that calculated the changes in the natural convection-induced airflow through Cave 6 that would occur in response to obstructions to airflow presented by cracks and doors in the shell of the present wooden building in front of that cave. Then they calculated the airflow and particle removal that would occur if filter material were used in place of the paper windows in the door panels of the present structure in front of Cave 6, as shown schematically in Figure 6.

The first two lines of Table 2 are again the uncontrolled base case with no structure in front of the cave and the case where the cave operates as it is today, respectively. The next line in Table 2 shows the amount of control one would exercise if the doors at the ground level and the balcony doors and/or windows on the upper floors of the building in front of Cave 6 were kept closed at all times. Airflow in and out of the cave would then flow through the existing cracks around the door and window panels. Our model suggested that in this case the average flow of air into Cave 6 under the conditions of 15–16 April 1991 would be 26 $m^3\ min^{-1}$, as opposed to 99 $m^3\ min^{-1}$ for the cave as it is operated today with doors open during the day but closed at night and with several door panels left

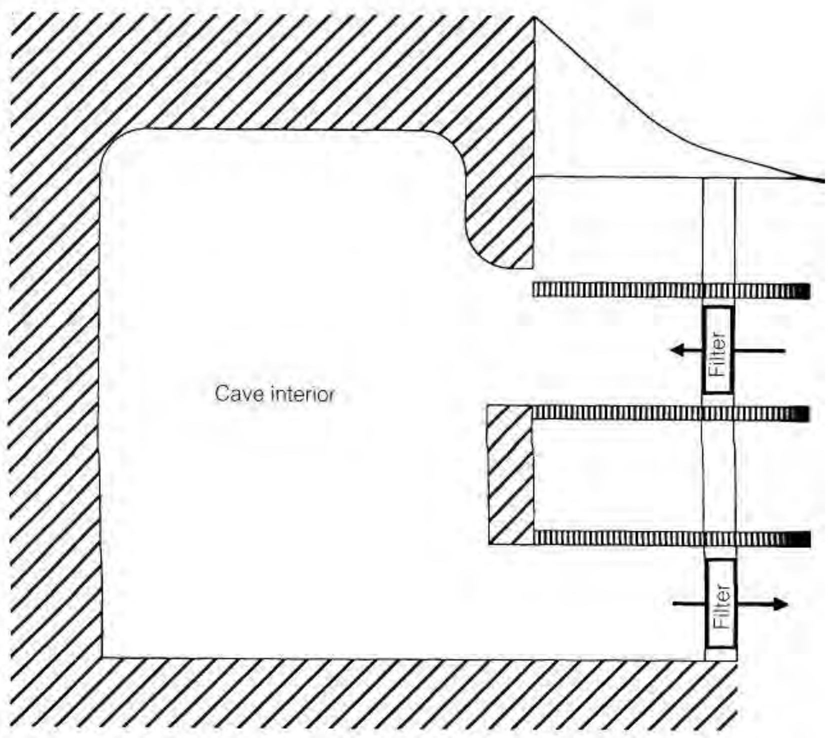

Figure 6
Schematic diagram of a passive air-filtration system, showing placement of filter material in the outer wall panels of a shelter in front of a cave at Yungang.

Table 2 Effect of alternative passive filtration system designs on reducing the particle mass flux to horizontal surfaces within a cave the size of Cave 6 at the Yungang grottoes[a]

	Air flow through cave ($m^3\ min^{-1}$)	Mass deposition to horizontal surfaces ($mg\ m^{-2}\ day^{-1}$)	Percent remaining relative to base case	Time to 100% coverage by particles (years)
Base case				
(1) Temple front removed	317	262	—	0.28
(2) Historical case with wooden building	99	139	53	0.47
Tightening up the wooden building				
(3) Closed doors[b]	26	50	19	1.0
Filter material installed in place of paper windows				
(4) Building still leaks[c,d]	34	45	17	1.2
(5) Building has no leaks[c,e]	6.3	3.4	1.3	9.0
Maximum amount of filter material installed				
(6) Building has no leaks[f]	86	7.5	2.9	6.3

[a] Values shown are averages of model predictions over the two-day period of 15–16 April 1991, for which data are available to drive the deposition model. Deposition rates under annual average conditions are about four times higher than under 15–16 April 1991 conditions; deposition fluxes shown above should be scaled upward proportionately and the times to reach 100% coverage by particles should be divided by a factor of 4 when considering time periods that approach a year or longer.

[b] The only control measure in this case is to ensure that the doors at the ground-floor level as well as balcony doors and windows on the upper floors remain closed at all times.

[c] Filter material with low-pressure drop characteristics is installed on the available window panels on both the ground floor and the third floor in the place of the existing paper windows. The pressure drop and efficiency characteristics of Minnesota Mining and Manufacturing, Inc. filter type GSB-30 have been used in these calculations.

[d] The doors on the ground floor as well as windows and balcony doors on the upper floors are assumed to remain closed at all times, but there is infiltration of air through cracks around the doors and windows of the building shell. Calculations show that 71% of the total mass of air that enters the cave does so through the cracks. Filter area both on the ground floor and the third floor level totals 2.56 m^2 at each level.

[e] In this case the cracks in the building shell have been caulked and all air entering the cave must pass through the filter material. Filter area both on the ground floor and the third level totals 2.56 m^2 at each level.

[f] Same as in Note *e*, except now the filter material has been increased: 55.4 m^2 filter surface area is supplied on the upper floors and 46.0 m^2 filter surface area on the ground floor. This is consistent with the filter surface area that could be incorporated into a new shelter in front of a cave, but exceeds the amount of filter surface area that can be incorporated into the historical wooden building in front of Cave 6.

open on the upper floors, and 317 $m^3\ min^{-1}$ for the case if the temple building in front of the cave did not exist. If all doors in the present building were kept closed at all times, particle deposition onto horizontal surfaces within the cave would be reduced by about 81% relative to the hypothetical situation where the cave has no wooden structure in front of it and thus is completely open to the atmosphere, as is the actual case for the great majority of the caves at Yungang.

Next to examine is the passive filtration alternative in which filter material would be placed into the panels that exist around the surface of the shelter in front of Cave 6. Here are three subcases:

Subcase 1

All doors in the building would be kept closed but there would still be leakage of unfiltered outdoor air into the cave through cracks around the doors and/or window panels. Specially selected low-pressure drop filter material (type GSB-30, sold in China by Minnesota Mining and Manufacturing, Inc.) would be used to replace the paper that presently covers the windows in the wooden temple structure at the ground-floor and third-floor levels, leaving the appearance of the existing wooden building virtually unchanged. In Table 2, line 4, it is seen that this would not offer much

further improvement, with 17% of the mass of deposited particles relative to the base case still remaining. The reason for this is that, of the 34 m^3 min^{-1} of air that enters the cave, 24 m^3 min^{-1}, or about 71%, of the flow into the cave would still pass unfiltered through the cracks in the building shell, and only the remaining 29% of the flow would pass through the filter material. The available filter cross-sectional area in this case is assumed to be equal to 2.56 m^2 each for both the downstairs and the upper levels of the wooden building front. This value is chosen because it is approximately equal to the cross-sectional area of the paper that exists behind the open latticework of the panels in the ground-floor level at the front of the present wooden temple structure.

Subcase 2

Filter material would be used to replace the paper windows in two floors of the existing building, as in the previous case, but particle deposition would be greatly reduced by caulking all cracks in the building shell, thus forcing all the air flowing into the cave (in this case about 6.3 m^3 min^{-1}) to pass through the GSB-30 filters. As seen in line 5 of Table 2, the mass of particles deposited onto horizontal surfaces within the cave would then be only about 1% of the base case. Again, 2.56 m^2 of filter material is placed in both the upstairs and ground-floor surfaces of the existing temple front panels in this case.

Subcase 3

The very low airflow rate into and out of the cave in subcase 2 above could cause problems if air exchange rates affected the rate at which water vapor (arising from water seepage through the cave rock surface, which damages the sculptures) is exhausted from the caves. Therefore, an ability to move air in and out of the caves at volumes like those observed historically may be desired. This can be achieved by increasing the cross-sectional area available for placement of filter material in the surface of the building panels. This may be impractical at Cave 6 given the historical character of the present wooden temple building in front of that cave, but if new shelters were constructed for other caves that presently lack any shelters, then provision for placement of greater amounts of filter material in such new structures could be considered. Preliminary design studies performed by Sedlak (1991) suggest that modified shelters could be erected in front of the caves that currently do not have them, with a design that would allow for a surface area of 46 m^2 (at the ground level) and 55.4 m^2 (at the upper floors) for filter placement, in the face of a building the size of the one in front of Cave 6. Line 6 in Table 2 examines such a case, using a cave with the dimensions of Cave 6 and a shelter constructed without significant air leaks between panels, and with air locks at the entry doors to suppress infiltration of untreated air as doors are opened and closed. Using this greater exposed area of filter material, 86 m^3 min^{-1} of air would enter the cave. We see then that 97% of the particle mass flux can be suppressed relative to a cave with no shelter in front of it, and the time necessary to completely cover an upward-facing horizontal surface inside the cave with

the first monolayer of dust would be increased to 6.3 years under conditions like those observed on 15–16 April 1991. Actual soiling rates will be faster than this because annual average deposition fluxes are higher than during the 15–16 April events available for model calculations. Still, a 97% reduction in particle mass flux would be effected relative to annual average conditions at an unsheltered cave, which is a substantial improvement.

Conclusions

A number of control alternatives have been identified in Tables 1 and 2 that would result in a major reduction in the rate of deposition of coarse particles inside the Yungang grottoes. One method employs a standard mechanical ventilation system with either high-efficiency filters, or low-efficiency filters—like filter F_{A3}—that are loaded with collected particles (easily achieved at Yungang). This method could reduce deposition rates on horizontal surfaces to 3–4% of historically observed levels, provided that air leakage into buildings in front of the caves can be kept to no more than about 3% of the uncontrolled airflow through an unsheltered cave, or no more than about 10% of the historically observed airflow through a cave like Cave 6 that has an existing wooden shelter in front of it. The degree of control in this case is really determined by the air infiltration rate achieved. If air infiltration could be eliminated, then reduction to less than 1% of the historical deposition rate could be achieved, but we view complete elimination of infiltration as unlikely. The best performance that can be obtained from a passive filtration system is a reduction to about 3% of uncontrolled deposition rates for the case of a tightly constructed new shelter in front of a cave with approximately 100 m^2 of filter material incorporated into the outer surfaces of that building.

Choosing a control system for the grottoes is not an easy task. Although the 96–97% coarse particle deposition control efficiencies of fairly simple systems sound impressive, the outdoor air at Yungang is extremely dirty. As seen in the far-right column of Table 1 and of Table 2, the time required to produce 100% coverage of a horizontal surface at Cave 6 is less than one-half year at present. That first monolayer coverage by particles probably is sufficient to produce most of the objectionable visual character of the soiling problem. Beyond a full monolayer coverage by dust, the deposits simply get deeper. Indeed, much less than a full monolayer coverage by particles is noticeable to a human observer. A 0.2% coverage by dark particles on a white surface is detectable if one looks very closely (Hancock, Esmen, and Furber 1976), and a 1% coverage can be seen easily at close range. The exact point at which visitors viewing the statues from a distance would notice the soiling is not known, but it is surely less than the point at which 100% surface coverage is reached.

The time needed to accumulate the first full monolayer of deposited particles, either in the presence of several possible mechanical air-filtration systems with reduced (but not zero) air infiltration or in the presence of the most promising passive filtration system, is about six to eight years under 15–16 April 1991 conditions, and up to four times faster under annual average conditions (see lines 7, 8, 11, and 12 of Table 1 and

line 6 of Table 2). Noticeable soiling would occur in less time. Given the time and effort needed to clean and restore a cave once it gets dirty, such a high remaining particle flux may be unacceptable.

The alternative to accepting such rates for recurrence of 100% coverage of the horizontal areas of the statues would involve an all-out attack on the problem, including (1) careful attention to making any new buildings in front of the caves as airtight as possible, forcing nearly all air exchange through filters (air must still be exchanged with the outdoors through filters in order to exhaust water vapor that leaks through the rock walls of the caves, and stopping air exchange completely by sealing the caves could be disastrous); (2) selection of the best passive filtration system or mechanical filtration system that can be supported; and (3) suppression of the local outdoor dust sources, as described earlier.

One could also study the effect of control of local coal smoke and regional outdoor air pollution sources other than the local road dust and soil dust, if the State Bureau of Cultural Relics or the Yungang grottoes staff believe that such a control program would be possible.

In conclusion, several questions need to be resolved: At what point is an unacceptable level of soiling of the statues reached? Is it as little as the first point where a close observer would notice the soiling, or is it as much as a full monolayer of dust or more? For how long must the statues remain cleaner than this unacceptable level of soiling?

Once these questions have been answered, the methods developed during the present analysis can be used to support the selection of an actual control system.

Acknowledgments

This work was supported by a research agreement from the Getty Conservation Institute. The cooperation and assistance of the staff of the Yungang grottoes and the State Bureau of Cultural Relics are gratefully acknowledged, including Huang Kezhong, Zhu Changling, Sheng Weiwei, Li Xiu Qing, Li Hua Yuan, Xie Ting Fan, Yuan Jin Hu, Huang Ji Zhong, and Zhi Xia Bing. The authors also extend their thanks to Bo Guo Liang of the Shanxi Institute of Geological Sciences, and Zhong Ying Ying from Taiyuan University. Assistance critical to this work was provided by the Getty Conservation Institute and its consultants, and we especially thank Neville Agnew, Po-Ming Lin, Shin Maekawa, and Roland Tseng for their help.

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Microclimate of Cave Temples 53 and 194, Mogao Grottoes

Sadatoshi Miura, Tadateru Nishiura, Zhang Yongjun, Wang Baoyi, and Li Shi

Since 1986, the Tokyo National Research Institute of Cultural Properties and the Dunhuang Academy have worked together for the conservation of the Mogao grottoes at Dunhuang. An agreement for this joint project was signed in December 1990 and includes three types of research on the grottoes: an environmental study, an analysis of deterioration, and a conservation study. The following is based on the environmental study of two grottoes from 1988 to 1992.

The Mogao grottoes consist of 492 cave temples excavated in a cliff above the Daquan River. The caves are situated at three levels—upper, middle, and lower—and vary considerably in dimension. While some can accommodate only one person at a time, others are large enough for many visitors.

The hypothesis was that different kinds of deterioration are caused by the different climatic conditions that may exist in certain caves. Caves 194 and 53 were chosen for measurement (Fig. 1). As Cave 194 is located on the upper level of the cliff and Cave 53 is on the lower level, the two caves were assumed to have different microenvironments, which would lead to different kinds of damage to their wall paintings (Miura et al. 1990).

Cave 194 is rather small. Its dimensions are approximately 3.6 × 3.6 m in depth and width, with a height of 3.3 m. The grotto has an antechamber and a lateral grotto, known as Cave 195. The paintings in Cave 194 are mainly from the Tang dynasty and are still intact today. Many small areas of flaking are found by careful observation, however, as well as blistering of the paint surface.

Cave 53 is large, with dimensions of about 6.5 × 6.5 × 6.5 m. It also has a lateral grotto, Cave 469, the entrance of which was sealed during the measurement period. Sand to a depth of several meters had covered the floor of Cave 53 until the 1960s. In the past, river water had often entered through the front of the cave, giving rise to humid conditions that caused flaking of the paint and black spots on the lower part of the wall.

Measurements

The microclimates of the two grottoes have been measured since March 1988 to investigate the causes of deterioration. Figure 1 shows the location

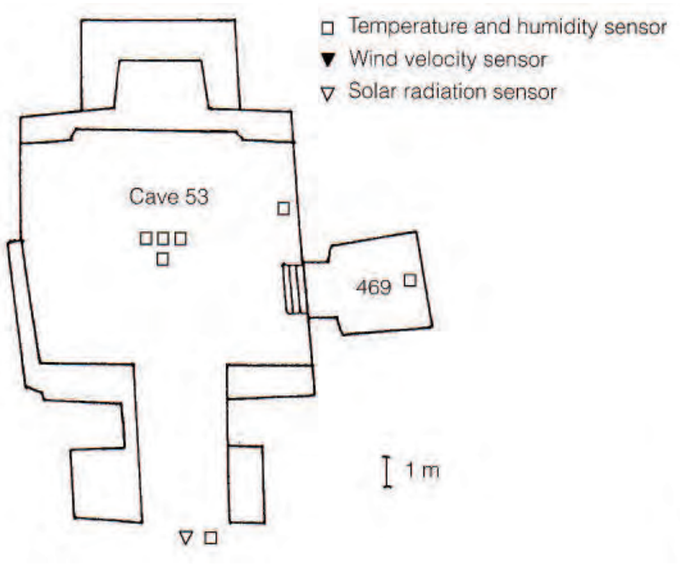


Figure 1
Plan of Caves 53 and 194.

of sensors. Temperature and humidity have been measured at three different heights at the center of each grotto. Since May 1991, temperature and humidity have also been measured inside a hole drilled in the ceiling of Cave 194 and in the floor of Cave 53.

Climatic data were recorded in data loggers every two hours (twelve times a day) from March 1988 to May 1991 (Li et al. 1990), and every hour (twenty-four times a day) from May 1991. The data are collected by a portable computer at the grotto or at the laboratory of the Dunhuang Academy by a radio system.

Average, maximum, and minimum climatic values are calculated from daily data. Monthly and annual values are derived from these daily calculations. Since Cave 194 is heated by sunlight during the day, the temperature measured at the entrance of this cave does not represent a typical outside value. Temperature and humidity measurements at the entrance of Cave 53 are used, therefore, as the external values for both grottoes.

Internal-external differences

Annual temperature changes within the grottoes were found to be less than the changes in temperature outside (Miura et al. 1992). Daily temperature and humidity changes in both grottoes were also less than those of outside. Only the annual humidity change did not show this tendency.

Even though Cave 469 is sealed from the outside, its humidity varies more than that of Cave 53 (Miura et al. 1992). This fact suggests that heat from outside is isolated by the rock but that moisture from outside (rain or groundwater) still affects the inside humidity via the rock.

Vertical differences inside the grottoes

The grottoes have an internal vertical temperature difference of about 4–5 °C from floor to ceiling on monthly average. It is interesting that the daily amplitudes of temperature at ceiling and floor depend on the season. Daily temperature at the ceiling changes more in summer (2.6 °C in July)

and less in winter (0.3 °C in January), whereas daily temperature at the floor varies in reverse (0.3 °C in July and 2.7 °C in January). This indicates that warm outside air enters a grotto along the ceiling in summer, and cold outside air enters over the floor in winter. A slow airflow was actually observed at the floor of a corridor of Cave 194 in winter. Air also circulates inside the grottoes, and its direction of flow changes according to the season.

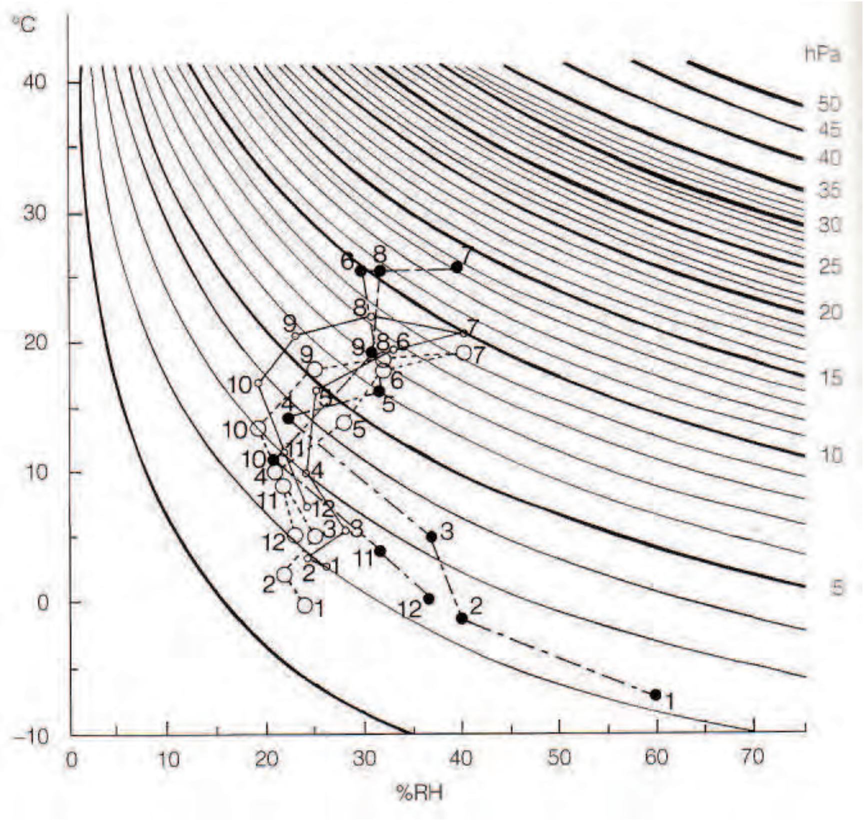
Differences between grottoes at different levels

The average temperature of Cave 194 is higher (about 2 °C) than that of Cave 53 (Fig. 2). Evidently the rock layer above Cave 194 is not thick enough to insulate the grotto from the heat of the sun.

One hole was drilled in the ceiling of Cave 194 and another in the floor of Cave 53 to study the microclimate in detail. Results show that humidity in both holes is high throughout the year (Fig. 3). Although the temperature in the hole of Cave 53 was more stable than that measured in the grotto itself, the temperature in the hole of Cave 194 was higher than that measured elsewhere in this grotto, which demonstrates the heating effect of sunlight on this cave.

The absolute humidity (moisture content in air) measured in the two holes was always higher than that of the outside air (Fig. 4), which indicates that the rock is more humid than the air. In particular, the hole in the ceiling of Cave 194 is much more humid than the hole in the floor of Cave 53. This would be very strange if the moisture had come from the river, because Cave 194 is located about 20 m higher than Cave 53 and

Figure 2
Climatograph of Caves 194 and 53: indicates outside data, represents the inside of Cave 194, and represents the inside of Cave 53.



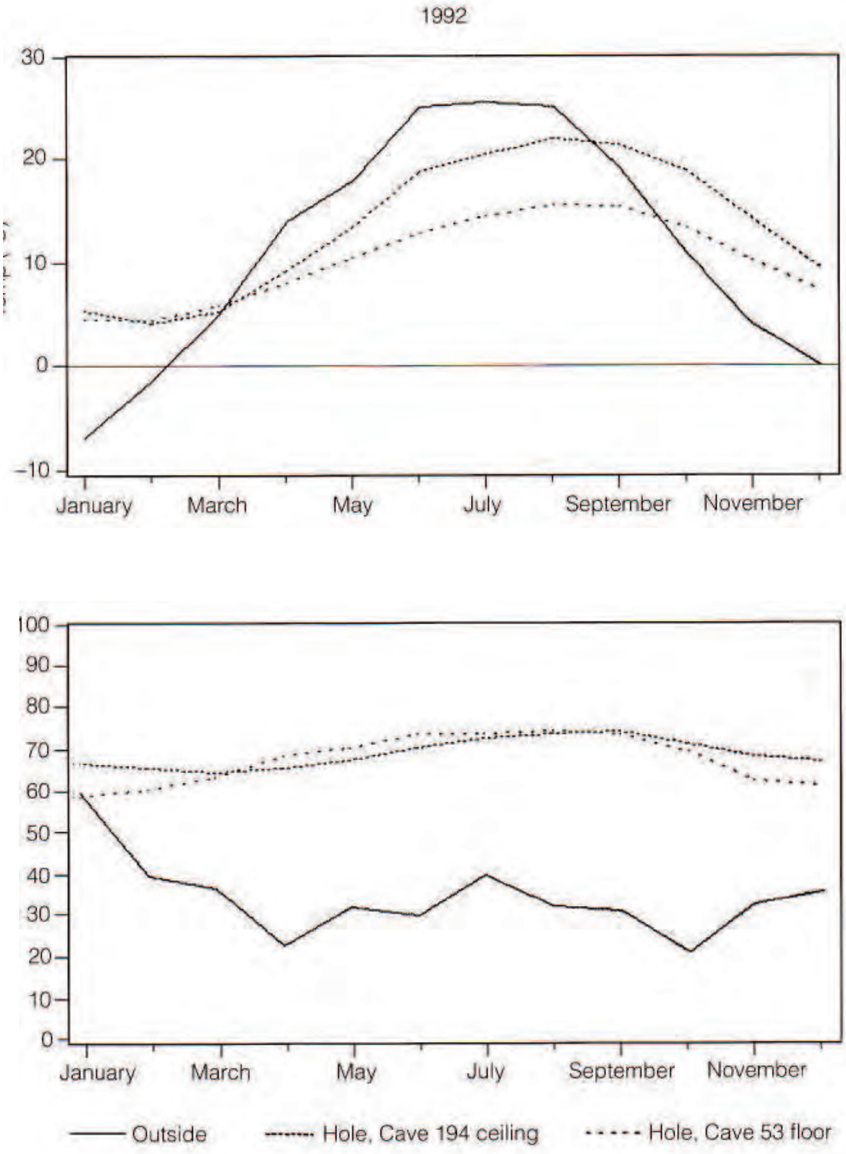


Figure 3
Temperature and humidity measurements taken in the holes in the ceiling of Cave 194 and the floor of Cave 53.

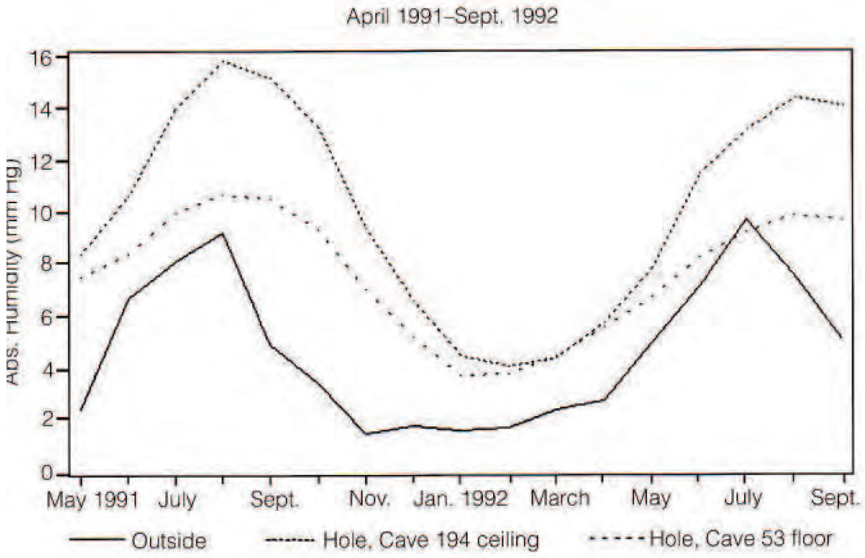


Figure 4
Absolute humidity measurements taken in the holes.

30 m above the river. An explanation may be found in Figure 5, which shows that the seasonal change in absolute humidity corresponds to the amount of rainfall.

The following conclusion was made: Rain soaks into the ground above the cliff and collects on the rock roof above Cave 194, since it is located below a small depression. The permeating rainwater carries soluble salts, which are found in high concentration in the surrounding sand and rock, into the grotto. The soluble salt, halite (NaCl), effloresces on the surface of the wall paintings when the water evaporates (Kuchitsu and Duan 1992), and damage to the paintings, such as blistering and flaking in spots, takes place. Since rainwater comes from the top of the cliff, the damage is more severe on paintings near the ceiling.

One early restoration attempt caused unexpected damage to the paintings. Decades ago, some of the areas affected by flaking were treated with a white mortar. After this intervention, damage by rainwater increased because water could not penetrate the mortar. More water evaporated from the surface of the paintings, and more efflorescence resulted.

Between 1961 and 1980, Dunhuang experienced heavy rain and flooding once. From a statistical analysis of climatic data during that period, a maximum rainfall of more than 20 mm day^{-1} probably occurs about once every fifteen years in Dunhuang (Fig. 6) (Takahashi et al. 1994). Such heavy rainfall can cause major damage, and it is important to protect cave paintings from these occasional events.

Conclusions

This study shows the influence of rainfall and groundwater on the microclimate of the grottoes. The following conclusion is derived from the two caves studied: Cave 194, located at the upper cliff level, suffers damage from efflorescence of halite as a result of moisture infiltration from above and migration through the rock. Cave 53, located at the lower level, shows efflorescence of a different salt: gypsum (Kuchitsu and Duan 1993),

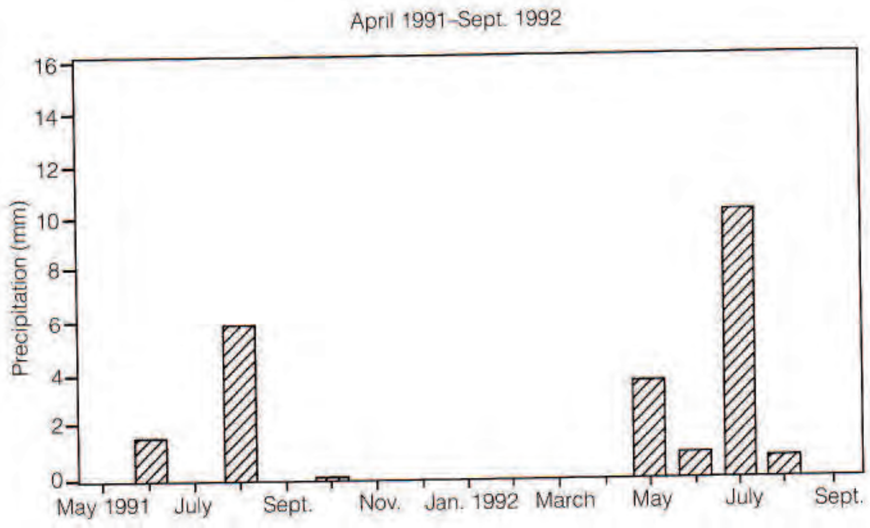


Figure 5
Rainfall data at Mogao grottoes from April 1991 to September 1992.

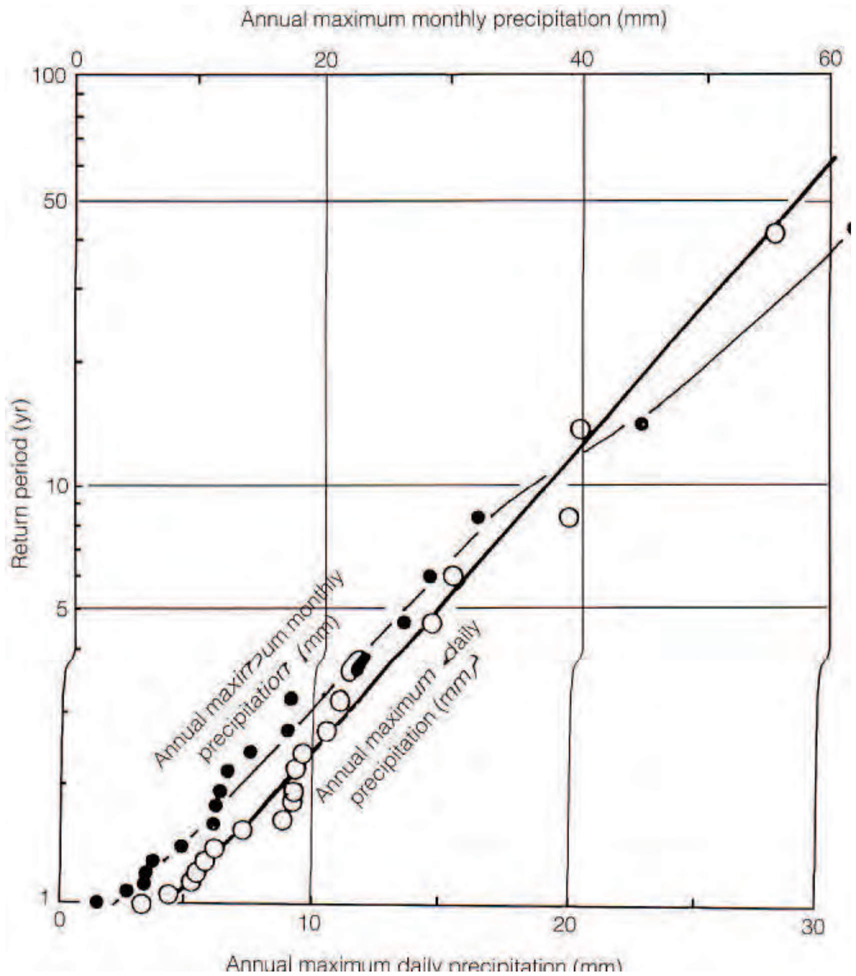


Figure 6
Return period of annual maximum monthly and annual maximum daily precipitation.

which may be produced by reaction between river water and soil when flooding occurs.

Thus, the wall paintings in these grottoes deteriorated mainly because of water, even though Mogao is located in a desert region. Rainwater moves through the rock of a grotto, then evaporates from the surface. Seasonal air circulation in the grottoes probably accelerates evaporation. This process causes flaking of the wall paintings in spots by efflorescence of soluble salts.

Protection from rainwater is important, especially for Cave 194. Installing a drainage system at the top of the cliff may be one effective means of conservation. Inadequate measures that may accelerate deterioration should be avoided.

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Environmental Monitoring at the Mogao Grottoes

Shin Maekawa, Zhang Yongjun, Wang Baoyi, Fu Wenli, and Xue Ping

The Mogao grottoes are located approximately 25 km southwest of the city of Dunhuang in Gansu Province in Northwest China, between the Gobi and Takla Makan deserts. Situated along the ancient Silk Road, it maintains one of the world's richest collections of Buddhist murals and statues dating back from the fourth to thirteenth century C.E. The caves were excavated in various sizes and shapes into a natural cliff approximately 30–50 m high, running roughly north-south. The rock consists of a soft, poorly cemented, coarse conglomerate. In the 492 decorated grottoes, mud plaster mixed with straw was laid directly on the conglomerate surface, and a white ground–paint layer was applied prior to the application of the succeeding paint layers.

Over the centuries, the priceless Buddhist artifacts, wall paintings, and clay sculptures in the grottoes were constantly subjected to looting or deliberate defacement. The Dunhuang Academy was established at the site in 1944 to protect the sites and conduct research on the history and culture of the Dunhuang region. The recent economic boom, political change, and widespread cultural awareness of the Asian region have facilitated a sharp increase in the number of tourists visiting the site (Fig. 1). The large number of visitors could change the microclimate of the caves, which can be deleterious to the murals and statues; continued high relative humidity levels produced by visitors may allow growth of fungi and bacteria, which could lead to permanent staining of the wall paintings (ASHRAE 1993; Torraca 1984:1–18). On the other hand, an extremely dry microenvironment in the caves resulting from the intrusion of dry desert air may desiccate the paint layers, resulting in flaking of the painted surfaces (Maekawa 1993:616–23). Fatigue failure of the paint layers may result if the wall paintings are subjected to large daily variations of temperature and relative humidity. Large numbers of visitors could also produce a high enough concentration of carbon dioxide in the caves to be unsafe for the visitors themselves (ASHRAE 1993). Furthermore, the combination of the high relative humidity and carbon dioxide could result in formation of carbonic acid, which could alter the painting surface.

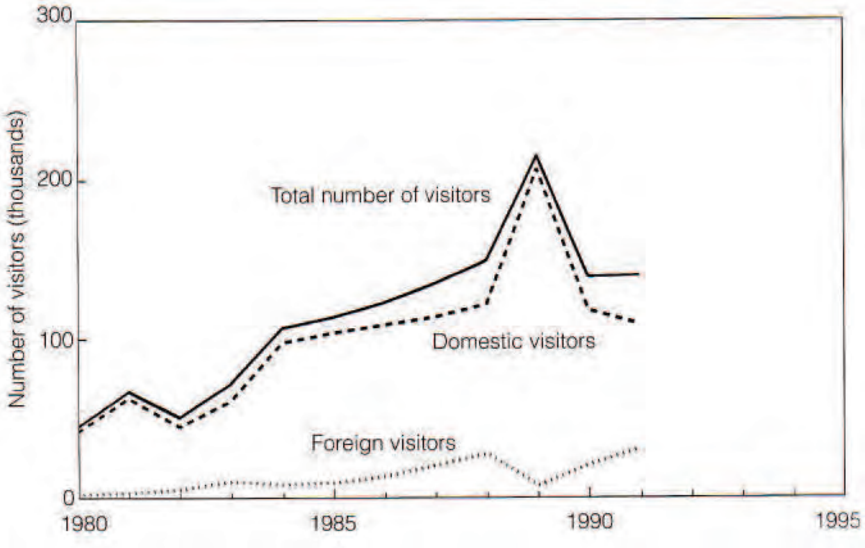


Figure 1
Number of domestic and foreign visitors at the Mogao grottoes between 1980 and 1991.

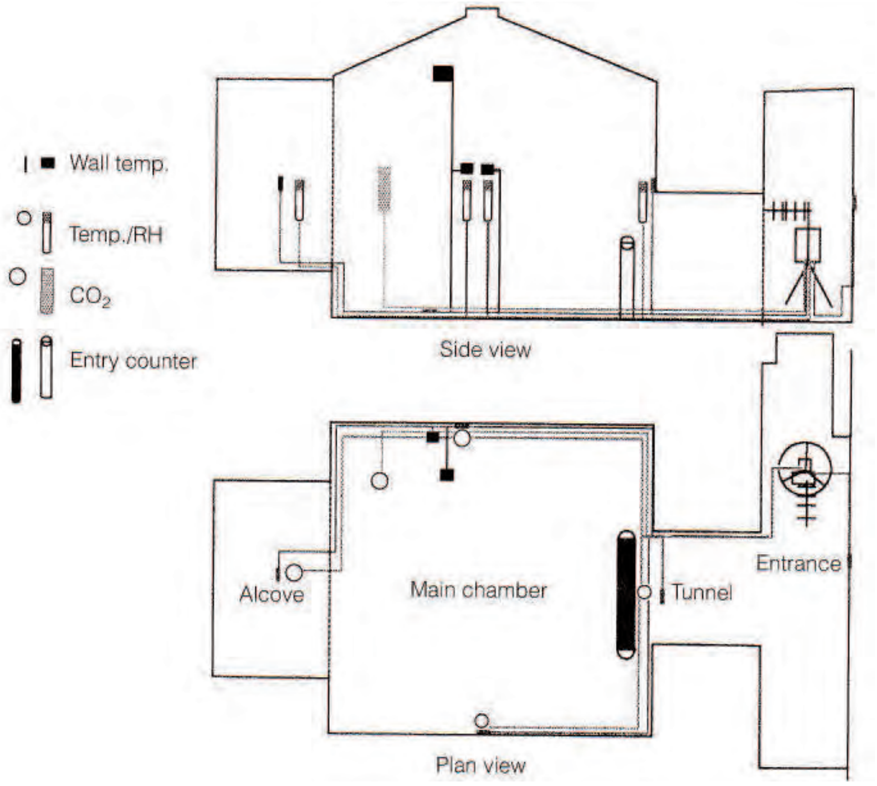
Objectives

Before any conservation work on a monument can be planned, basic information on the natural and fabricated environments affecting the site is needed. In the case of the grottoes, a dry desert climate combined with the stable microenvironment of caves contributed to the survival of the wall paintings and sculptures. However, the constant increase of visitors may be altering the microenvironment. Thus, in addition to general information on the climate of the site and microclimate of the caves, information was gathered about the effects of visitation on the caves' microenvironment: changes in cave temperature, relative humidity (RH), and carbon dioxide content. The number of visitors and their length of stay in the caves, as well as the months of maximum cave visitation, were also important factors to be documented. The ultimate objective of the environmental monitoring was to develop strategies to reduce the effects of visitors on the microenvironment of the grottoes.

Model Caves

Two architecturally similar, medium-size caves, Caves 323 and 335 (Fig. 2), were selected to document effects of visitors on the microenvironment. Both are located at ground level (there are no caves below them), oriented east to west. As indicated in Figure 2, each cave consists of a main chamber of about 125 m^3 with an alcove of approximately 25 m^3 and an entrance area of approximately 24 m^3, connected by a short tunnel approximately 2 m high, 1 m wide, and 2 m long. Each cave has been fitted with a wall made of aluminum sheets on which two hinged doors, approximately 1 m wide and 1.8 m high each, are mounted in the middle. Both the wall and doors are made with fixed-angle louver openings. In 1989, as part of the collaborative conservation project of the Getty Conservation Institute and the Dunhuang Academy, a filter material was installed over the openings of the caves to protect against the intrusion of airborne sand and dust. The material used was a nonwoven, spun-bound, lightweight

Figure 2
Schematic of Caves 323 and 335.



geotextile. Thus, it was expected that air exchange rates would be significantly reduced. Cave 323 was normally open to visitors for eight hours each day, and thus became the test cave. Cave 335 was closed to visitors, and served as the control.

Monitoring System

Three autonomous, environmental monitoring stations (one meteorological and two cave stations) and a base receiving station were installed (Figure 3 shows their locations). The meteorological station for collecting area-wide climatic data was located on top of the 35 m high cliff near the center of the site and approximately 200 m from the base station, which was set up at the Dunhuang Academy's laboratory building on the site. Cave stations were configured to gather information within the environment of the individual caves, which are approximately 250 m north of the meteorological station. The retrieval procedure for the accumulated environmental and microenvironmental data consisted of periodically transmitting the data collected at each station via UHF radio to the base station, where they were transferred to microdiskettes. These diskettes were then mailed to the Getty Conservation Institute in California for statistical analysis.

Figure 3
Map of the Mogao grottoes and locations of monitoring and base stations.

Continuous monitoring

Visitor groups seemed to spend about five minutes in Cave 323, since it is of medium size. Therefore, a two-minute interval was chosen to monitor environmental changes in Cave 323 and yielded at least two measurements during visitation periods. At night, when there were no visitors, the interval was extended to fifteen minutes to improve the efficiency of the data collection and maximize the equipment's capacity. Four sets of air-temperature, RH, and surface-temperature sensors were placed between the entrance and the alcove, at the deepest location in the main chamber of the cave. The air-temperature and RH sensors were mounted on self-standing glass panels (installed by the Dunhuang Academy to protect the paintings from being touched), positioned 20–30 cm from the walls. Each surface-temperature sensor was first adhered to an oversized strip of thin cotton gauze, then the perimeter of the strip was mounted on the painted surface using Paraloid B-72 adhesive diluted with acetone to ensure reversibility. An additional set of wall-temperature sensors was located 2 m from the floor and near the ceiling to determine any variation in wall temperature with respect to height. A set of infrared-photo sensors was placed at the entrance of the main chamber to log visitor entry and exit. Finally, a carbon dioxide monitor was positioned at the back of the main chamber. The same configuration of sensors, with the exception of the CO_2 sensor, which was omitted, was used in the control grotto.

Controlled experiments

The effects of visitor groups on the microenvironment of the caves were recorded through a number of controlled experiments conducted with the participation of visitors to the site. A group consisting of twenty to forty persons entered the main chamber of Cave 323 and stayed for thirty minutes while the entry doors were fully open. The group remained standing for the duration of the stay, then promptly exited. The entry door was closed immediately after exit. Three separate experiments were conducted to determine increases in the environmental parameters during the experiment and their subsequent decay.

Results of Environmental Monitoring

Climate of the site

The climate of the Mogao region is arid, with seasonal extremes of temperature. At the top of the cliff, the air temperature varies from −15 °C in February to 38 °C in July, with the daily minimum relative humidity ranging from 28% in February to only 10% in July. Throughout the day, the RH typically remains between 10% and 20% in summer months and 20% and 30% in winter months, except for the occasional passing of a moist air mass through the area, associated with movements of weather fronts in the region. The typical diurnal temperature variation is approximately 15 °C throughout the year. During the testing period, medium strength wind, averaging 5 m s^{-1}, was always present. The wind direction normally

shifted to the south and southeast during the day, and to the southwest at night. Gusty westerly winds generated dust storms in spring. The daily maximum solar radiation ranged between 1.0 kW m^{-2} in June and 0.4 kW m^{-2} in December. Rainfall was concentrated in the summer months of June, July, and August, with an annual total rainfall of about 25 mm. Snow was observed in the winter months, but accumulation was not recorded.

The microclimate of the site below the desert plateau, directly outside Cave 335 at the base of the cliff, was milder: −10 °C in February, 30 °C in July, and 17% RH in April versus 35% RH in August. The monthly average moisture content of the air (expressed in the humidity ratio, which is the weight of moisture in one kilogram of air at that temperature) ranged between 1.2 g of moisture per kg of dry air in January to 6.3 g of moisture per kg of dry air in August.

Microclimate of the control cave

Inside Cave 335, temperatures were more stable than outside, and the air temperature was higher (between 5 °C in February and 19 °C in August) while the low RH was 19% in January compared with a high of 42% in August. Air temperature was extremely stable throughout the day. Although the relative humidity was also relatively stable throughout the day, it varied day to day as it followed changes of the outside climate, particularly during summer. The average monthly humidity ratio of the air in the cave varied between 5.5 g of moisture per kg of dry air in August and 1.2 g of moisture per kg of dry air in February.

Surface temperatures of the cave walls remained only 1–2 °C higher in winter and 1–2 °C lower during summer than the temperature of the adjacent air. Therefore, the relative humidity of the wall surface, which was estimated from the moisture content of the adjacent air and the surface temperature of the wall, remained within 5% of that of the air. Temperature variations between floor and ceiling remained less than 1 °C; temperatures at the ceiling were higher than temperatures at the floor at all times. As expected, the influence of outside air was always greater near the entrance.

Microenvironment of the test cave

Visitors

Over 80% of the annual visitation total of forty-three thousand to Cave 323 was concentrated in the tourist season, between May and October, with the maximum number of visitors (thirteen thousand) in August. The number dropped to less than two thousand by October, and there were only small numbers of visitors in winter months, November through March. Figure 4 shows that in August there were occasionally up to eight hundred visitors per day. Figure 5 shows the distribution of visitors in an eight-hour day of operation during the busiest month, August. Admission to the cave is allowed between 8 a.m. and noon and between 2 and 5 p.m. On a daily basis, a large number of visitors visited the cave at about 9 a.m. and again at about 3 p.m. There were more visitors in the morning than

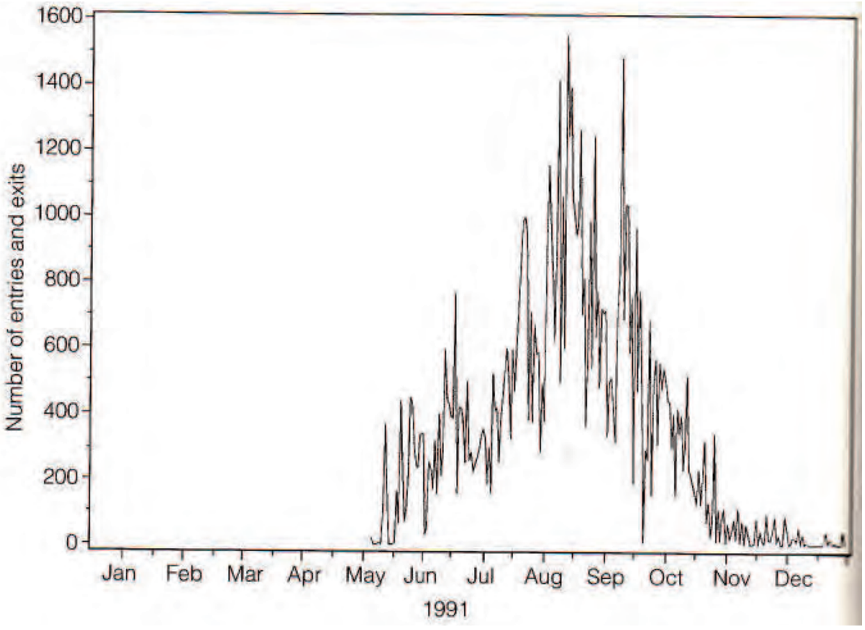


Figure 4
Daily total number of visitors to Cave 323 in 1991.

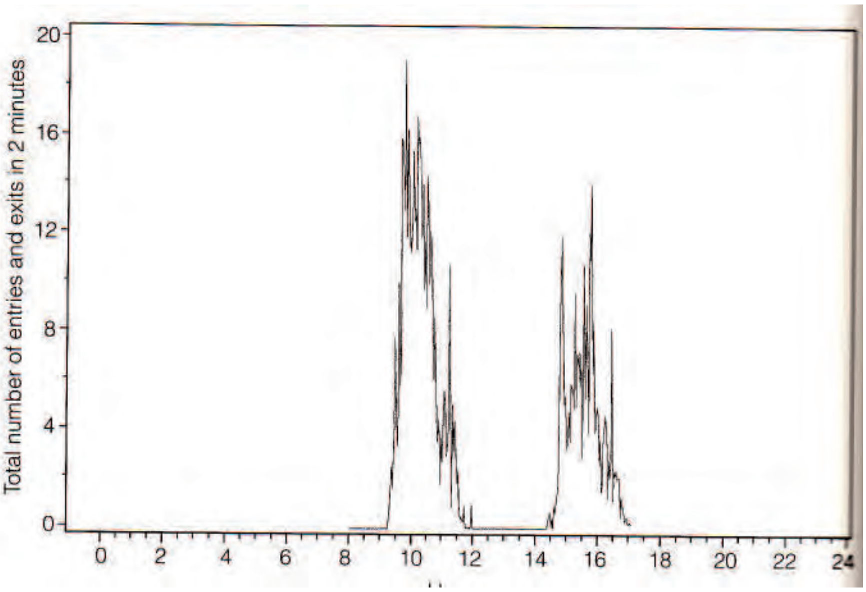


Figure 5
Daily distribution of visitors to Cave 323 in August 1991.

the afternoon, with an average of about six people per two-minute period around 10 A.M., while around 3 P.M. there were about two people per two minutes. The typical visit lasted about five minutes.

Air temperature

Figure 6 shows the daily extremes of air temperature in the cave. The smooth line connecting minimum temperatures indicates the natural air temperature change in the cave. The maximum temperatures exhibited extreme variations, particularly in the summer months when the greatest number of visitors tour the site, producing large daily variations in air temperature. Visitors always cause sharp increases in air temperature. Figure 7 shows the changes of air temperature between 8 A.M. and 5 P.M.

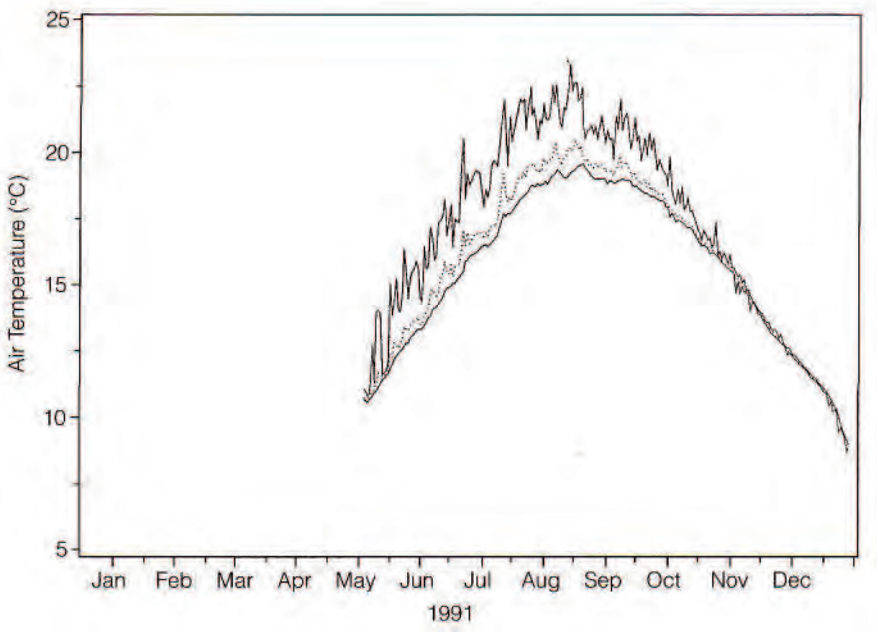


Figure 6
Daily extremes and average of air temperature in Cave 323 in 1991.

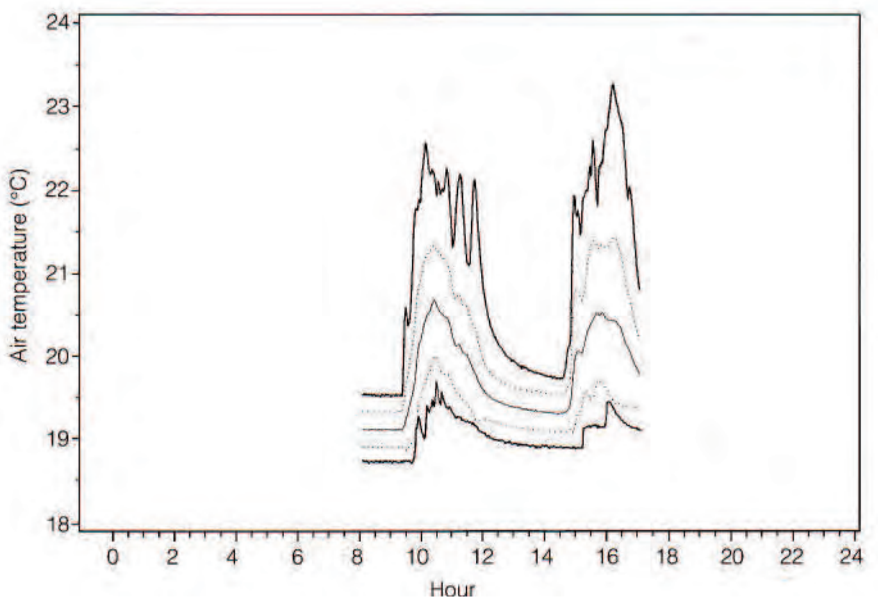


Figure 7
Daily changes of air temperature in Cave 323 in August 1991.

recorded in the visited cave in August 1991. Two peaks were recorded daily, and larger peaks were often recorded in the afternoon, although more visitors were logged in the mornings, indicating the strong effect of warmer, outside air. By the next morning in summer months, the temperature recovered to its natural level. Outside air temperature was always higher than the temperature in the cave during visitation hours. This resulted in increased air temperature in the cave whenever the entry door was opened.

Relative humidity

Daily extremes and averages of relative humidity in Cave 323 are shown in Figure 8. Unlike the relatively stable minimum air temperature in the cave,

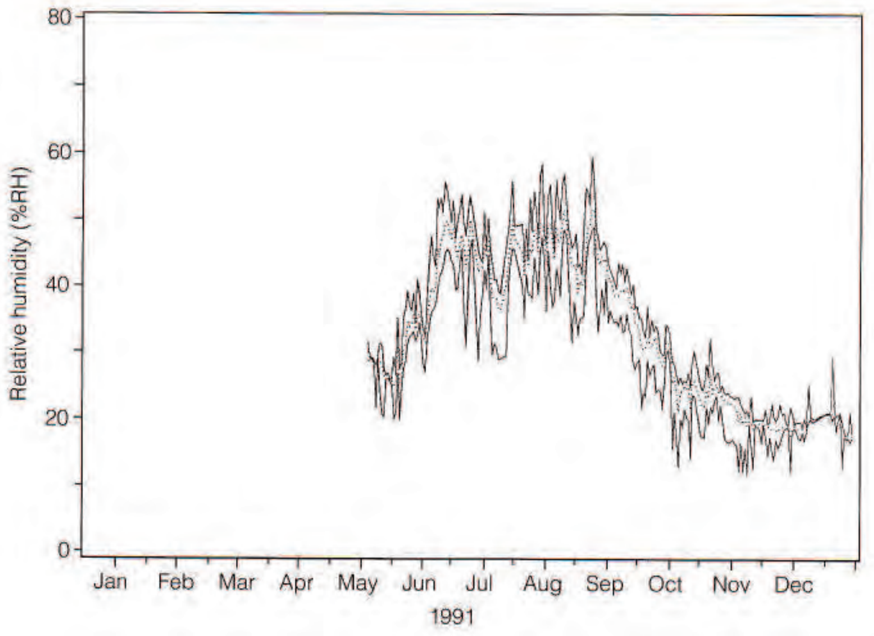


Figure 8
Daily extremes and averages of relative humidity in Cave 323 in 1991.

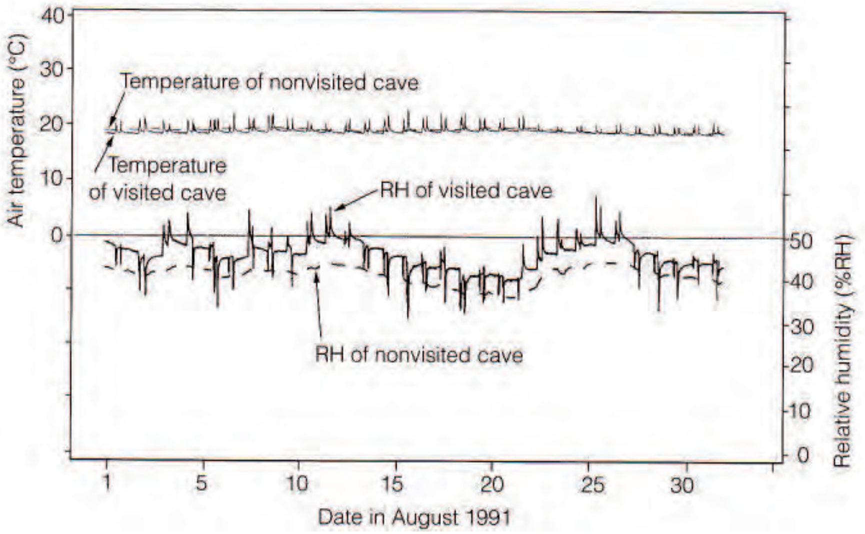


Figure 9
Air temperature and relative humidity changes in Caves 323 and 335 in August 1991.

large daily variations of both the maxima and minima were recorded. This indicates that the effect of visitors is not limited to the increased relative humidity, which was expected as a result of visitors emitting moisture in the cave. Figure 9 shows comparisons of temperature and relative humidities in the test and control caves in August 1991. The baseline relative humidity of the visited cave was approximately 5% higher than that of the nonvisited cave, although changes in the moisture content of the outside air were also tracked. Twice-daily spikes, ±3% to ±15% RH, correlated precisely with the morning and afternoon surges of August visitors.

In spite of the expectation that spikes in the relative humidity in the visited cave would always be positive, as respiration leaves moisture in the cave, the spikes were both positive and negative relative to the stable

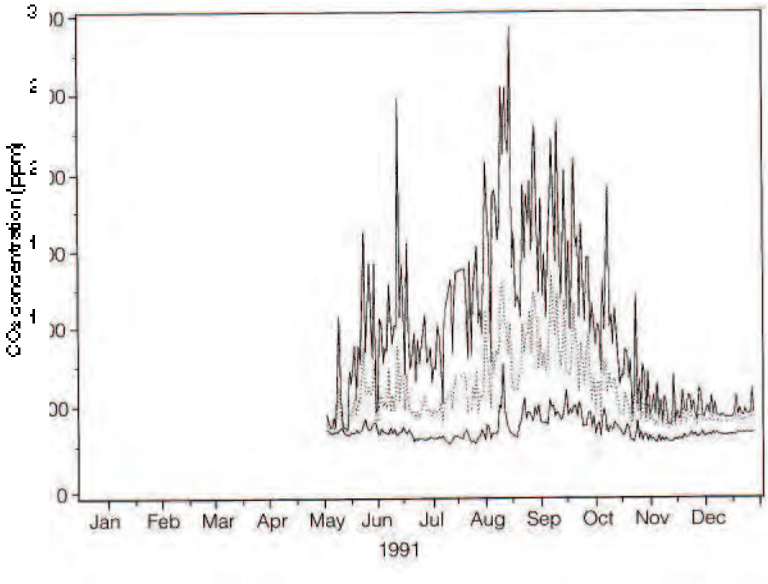


Figure 10
Daily extremes and averages of carbon dioxide levels in Cave 323 in 1991.

value, as seen in Figure 9. Negative spikes were always observed when the relative humidity in the cave was dropping for periods longer than a day; positive spikes were observed whenever the relative humidity was rising, which was due to changes of the moisture content of the outside air. The degree of influence of the outside climate on the microenvironment of the cave increased as the number of entries increased. The cause of these changes is due not only to the moisture released by the visitors, but also to the frequent opening and closing of the cave door and entry of visitors, which forced air exchange with the outside air.

Temperature of the wall surface

Temperature differences between the wall surface and the air adjacent to it were quickly lost when visitors entered the cave, causing air turbulence. The result is a loss of the wall's protective thermal boundary layers, which causes the wall temperature to become equivalent with the air temperature. This phenomenon eliminates the possibility of condensation on the wall surface even on a rainy day. Therefore, temperature difference was not considered important in this study.

Level of carbon dioxide

Daily extremes and averages of carbon dioxide in Cave 323 in 1991 are plotted in Figure 10. The maximum concentration of carbon dioxide, approximately 3,000 ppm, was recorded in August 1991. The concentration always dropped to less than 700 ppm by morning, even when daily maximums reached more than 2,000 ppm. As expected, increase in the carbon dioxide content of cave air correlated well with the distribution of visitors, rising from a normal level of about 400 ppm to an average of some 1,500 ppm in the morning (and a maximum of nearly 3,000 ppm) when the cave received the most visitors (Fig. 11). From these high values, carbon dioxide concentrations dropped to an average of 1,000 ppm in the late afternoon and then recovered to the 500 ppm level by the next morning.

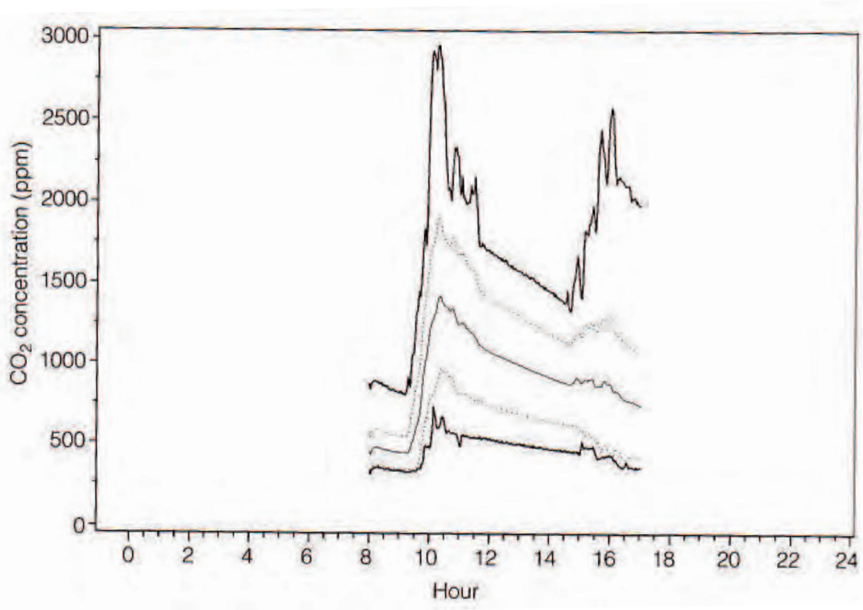


Figure 11
Daily changes of carbon dioxide levels in Cave 323 in August 1991.

Dust

The filter material mounted on the door openings was effective in eliminating the intrusion of windblown sand. However, the amount of airborne dust was insignificant in comparison to the amount of sand that was transported into the cave by visitors' shoes and clothes. A large volume of coarse, sandy dust, 0.1–0.5 mm in diameter, was found in the entryway to Cave 323.

Results of Controlled Experiments

Figure 12 shows monitored changes of the air temperature, relative humidity, and carbon dioxide during one of the controlled experiments conducted in Cave 323. Averages of the measured rate of increase of environmental parameters during the controlled experiments were approximately 90 ppm per hour per person, 0.3% RH per hour per person, and 0.3 °C per hour per person, for carbon dioxide, relative humidity, and air temperature, respectively. The increase of relative humidity corresponds to 50 g of water per hour per person and carbon dioxide to 0.1 m^3 per hour per person. Half-times of the parameters during their decays were approximately twenty-four minutes, two hours, and five hours in the first six-hour period for air temperature, relative humidity, and carbon dioxide, respectively. The half-time for carbon dioxide is equivalent to the air exchange of the cave. However, to completely recover the ambient level of relative humidity and carbon dioxide, it took more than one and two days, respectively.

A larger decay rate of relative humidity following the exit of the visitors, in comparison to the decay rate of carbon dioxide indicates the absorption of some moisture by wall surfaces of the cave. However, due to the large hygroscopic capacity and surface area of the cave wall, as well as the high volume of air exchange with the dry outside air, the

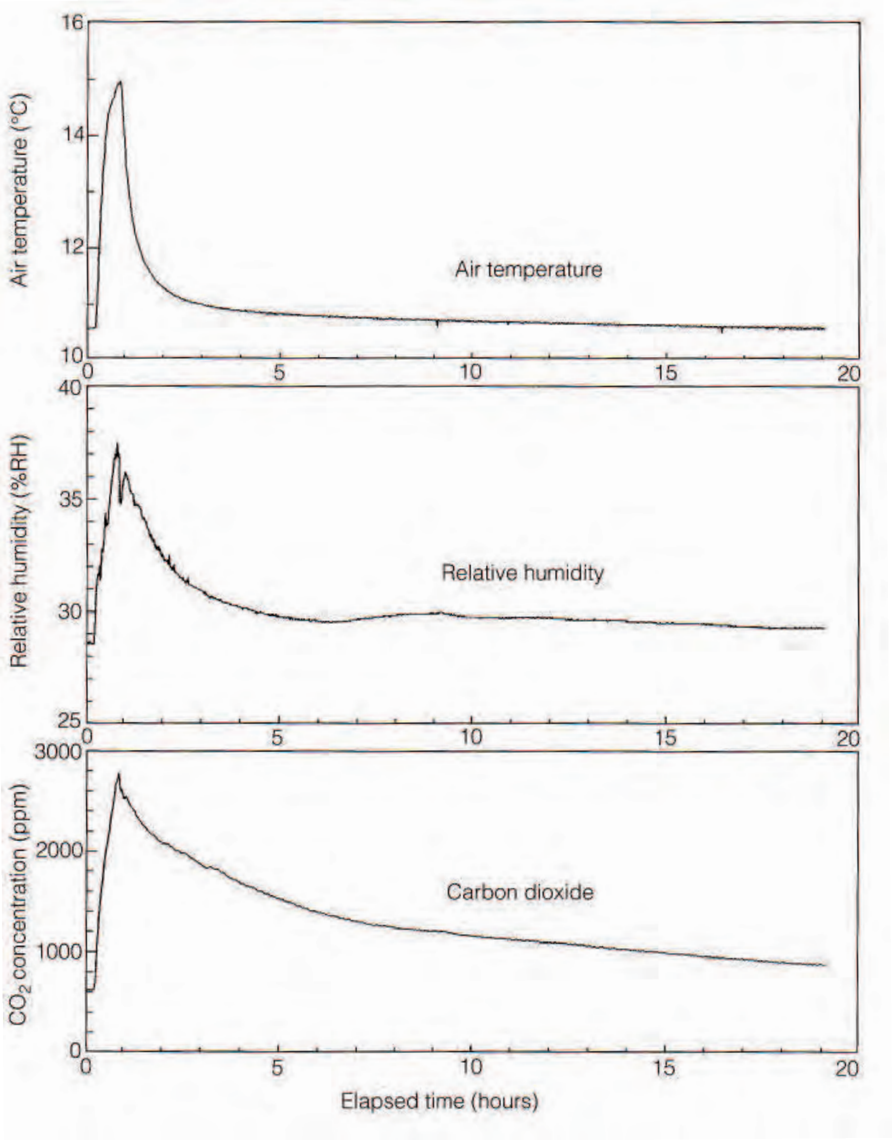


Figure 12
Changes of air temperature, relative humidity, and carbon dioxide during controlled experiments conducted in Cave 323.

release of 500–700 g of moisture generated by visitors did not result in a noticeable increase of the baseline relative humidity in the cave. Furthermore, the natural influx of outside air dominated the cave's relative humidity before its complete recovery from the experiments.

Conclusions and Recommendations

The air temperature of Cave 335, which was closed to visitors, ranged from a low of 5 °C in February to the high of 19 °C in August, and the relative humidity varied between 19% in winter and 42% in summer. Outside air temperature and humidity ratios varied between −10 °C at 1.2 g of moisture per kg of dry air in February and 30 °C at 5.5 g of moisture per kg of dry air in August. The cave's natural moisture was removed throughout the year through constant flushing by the dry outside air. Therefore, moisture removal will be significantly reduced and the stability of the microclimate improved if the caves' entry doors are tightly sealed and access is tightly restricted to limit air exchange with the outside. If a

cave is completely sealed, it will maintain the natural relative humidity and temperature of the bedrock conglomerate, which is between 60% and 70% RH at 11–15 °C (Miura et al., herein).

The historical value and artistic quality of the artifacts at the Mogao grottoes have recently attracted many visitors each year. This trend will probably accelerate with the majority of tourists continuing to come in July through September and most of the visitors touring the grottoes in the morning. Visitors remain in a medium-size cave for an average of five minutes. At the present level of visitation, sixteen thousand visitors toured Cave 323 in the month of August. A significant accumulation of heat, moisture, and carbon dioxide—which can increase the rates of deterioration of the wall paintings and sculptures in the cave—was not observed, even during the high tourist season. However, visits to the cave did result in increased air-exchange rates, producing more unstable conditions in the cave. The visitors unknowingly brought a large amount of sand into the cave on their clothing and shoes, producing a dusty environment.

Although daily variations in environmental parameters caused by the visitors dissipated overnight, these visits generated sharp, twice-daily spikes of air temperature and relative humidity to +4 °C and ±15%, respectively. These spikes were the result of large volumes of entrained outside air entering the cave as visitors entered. As expected, the spikes were larger near the entrance.

The presence of visitors often raised the carbon dioxide content of cave air to 2,000 ppm and occasionally to 3,000 ppm in August, although this figure always dropped to less than 750 ppm by the following morning because of the air-exchange rate. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) recommends a standard ventilation rate in public areas that will maintain the carbon dioxide level below 1,000 ppm (ASHRAE 1993). The continued entry of large numbers of visitors should be controlled, as undesirable health effects will result if the CO_2 level in a cave rises above 2,500 ppm.

Controlled experiments were conducted in Cave 323 to isolate the effects of a group of visitors on the microenvironments. The experiments yielded increased rates of temperature, relative humidity, and carbon dioxide during the group's stay as well as decay rates of these parameters following the visitors' exit from the cave. Generally accepted generation rates of moisture and carbon dioxide by adults (ASHRAE 1993) agreed with the measured values from the experiments. However, a large effect of entrained outside air during entry and exit was a major contributor of the perturbation of the microenvironment.

Twice-daily peaks of the environmental parameters can be controlled only by evenly distributing visits throughout the cave's open hours and limiting visitor access on days with extreme weather conditions, such as dust storms and heavy rain. Maintenance of the present air-exchange rate (approximately five hours during open hours) is important, as it is the only means of expelling moisture, carbon dioxide, and odor generated by visitors. The rate has been sustained even with the filter material—which had been installed to control wind-driven sand and airborne dust—

covering the louvers of the entry walls and doors. The unintentional transportation of sand into the cave by visitors can be easily controlled by requesting visitors to remove their shoes upon entry or placing a grate and floor mat outside of the cave.

Acknowledgments

The authors wish to thank Neville Agnew, associate director, programs, the Getty Conservation Institute, for his advice and discussion throughout the project. This work was conducted as an integrated part of the collaborative project between the State Bureau of Cultural Relics, the Dunhuang Academy, and the Getty Conservation Institute for the conservation of the Mogao grottoes.

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A Nondestructive Method for Determining Weathering and Consolidation of Stone

Zhong Shihang and Huang Kezhong

Natural weathering poses the greatest threat to exposed ancient stone statues, many of which are fine works of art. One method of preventing weathering is to treat the surface with a chemical consolidant. The consolidant should penetrate the surface and harden, thereby reinforcing it and increasing its strength and weathering resistance. The consolidant must satisfy the following conditions: (1) it must not change the appearance and color of the statue; (2) it must be able to penetrate the stone deeply enough so that the surface does not exfoliate and thereby accelerate damage; (3) it must allow water vapor to migrate freely into and out of the stone so that there is no accumulation of water behind the treated layer, which would accelerate damage to the statue; and (4) it must increase the strength of the treated layer to a considerable degree.

In addition to the selection of suitable chemical consolidants, nondestructive measurements of the depth of weathering and of penetration of the consolidant are critical. This problem has been solved by the development of an electrical resistivity method and the application of a C-1 microdepth measuring instrument.

Principles and Testing Validation

Electrical resistivity of a medium is directly related to its density and other physical properties. After weathering, the resistivity of rock undergoes great changes, and there are marked differences in the resistivity of the same rock type that has undergone both severe and mild weathering. Chemical consolidation also changes the resistivity of the rock. Therefore, measurement of resistivity can provide information on the depth of weathering and penetration of the consolidant. Even the depth of penetration of different components of mixed materials can be determined.

As shown in Figure 1, two electrodes, A and B, are attached to the surface of the rock, and a direct current of intensity I is passed into the rock. Electrodes M and N are attached at two additional points and the

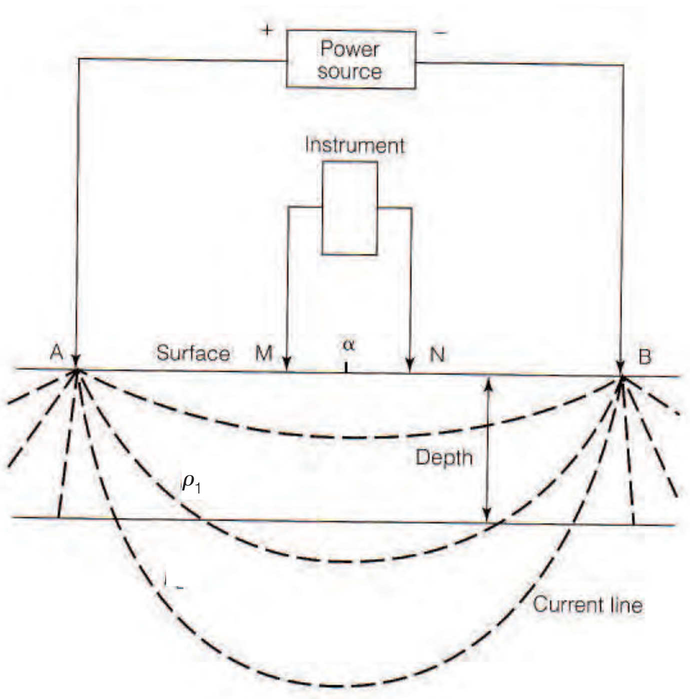


Figure 1
Principle of the resistivity method of weathering depth determination.

potential difference $\triangle V_{MN}$ determined. The resistivity, ρ_S, of the rock can be calculated by the formula

$$\rho_S = K \triangle V / I$$

where K is a constant calculated on the basis of the relative positions of A, B, M, and N, and ρ_S represents the conductivity of the medium at a certain depth. When the current at A and B is increased, the value of ρ_S reflects the increase in depth. The depths of layers of different resistivities can then be determined from a $\rho_S - h$ plot, where h represents depth within the stone.

This method is used to measure depth of weathering of rock and the penetration of the chemical consolidant. It can also be used for nondestructive determination of the thickness of, for example, a concrete layer on the surface of carved rock or the depth of a mud-plaster or lime-mortar layer.

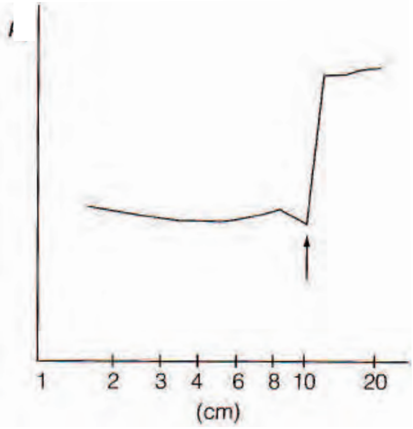


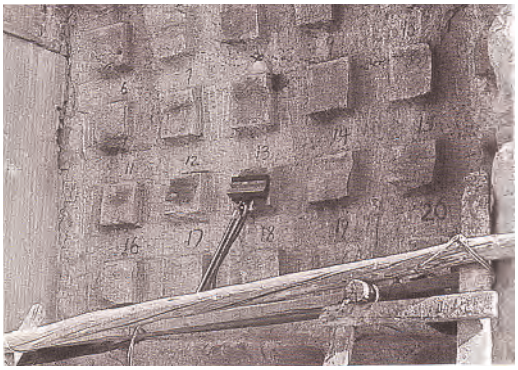
Figure 2
Resistivity curve to determine thickness of an applied layer of concrete on rock.

Figure 2 shows how the depth of a concrete layer over a rock surface may be determined. The curve compares the results of the method with measurements after drilling and corroborates the effectiveness of the method. Furthermore, since the thickness of the concrete layer ranged from 10 to 25 cm, the precision of measurement could be selected in a range of about 1 cm. A probe of measurement precision of 2–3 cm can therefore be used for measuring depths of weathered layers and of chemical penetration only 2–3 mm in thickness.

On-Site Measurements

A configuration of four symmetric electrodes was used for on-site measurements on carved rock surfaces. That is, A, B, M, and N were arranged

a



b

Figure 3a, b
On-site measurement: (a) instrumental setup; and (b) close-up showing attachment of electrodes.

in a straight line, so that A and B were symmetrical to the midpoint, O, between M and N; that is, AO = BO. Then,

$$K = 2\pi AM \cdot AN / MN$$

To facilitate measurement, electrodes were affixed in advance to an insulated frame according to predetermined sizes of AN and MN. To provide an adequate fit on uneven surfaces, each electrode group was spring-loaded for good contact with the surface. An electrode with a diameter of 2–4 mm is used to measure depth of about 10 cm; for measurements in the range of 2–3 cm with a precision of 2–3 mm, an electrode of 0.5–1 mm is used.

Because the contact resistance between the electrodes and the surface of the carved rock was found to be higher than 200 kΩ, ordinary measuring instruments could not be adapted. The C-1 microdepth measuring instrument developed by the authors was designed for a specific purpose, and normal determinations were possible even when electrode ground resistance was as high as 500 kΩ. The instrument is also light and convenient, and it consumes little electricity.

This nondestructive technique for determining the depth of weathering of rock and the depth of penetration of consolidants has been applied at the Yungang, Longmen, Kizil, and Dazu grottoes, as well as to the Leshan Buddha statue (Fig. 3a, b). Figure 4 is a curve measured at an experimental site at Yungang. The rock is sandstone, the surface of which was severely weathered. From the curve, it can clearly be seen that the weathering depth was 10 mm. This is consistent with the measurement taken from a cross section of this sculpture.

Figure 5 shows data on the depth of weathering of the sandstone measured on the body of the Leshan Buddha. A depth indicative of severe weathering can be clearly seen.

Figure 6 shows results from the surface of the sandstone adjacent to the foot of the Buddha on the northern wall of Cave 16 of the Yungang grottoes. An abundant accumulation of salt near the surface layer of the sandstone has caused severe weathering to a depth of 10 mm. At a depth of 20 mm, a distinct interface is present parallel to the peeling and

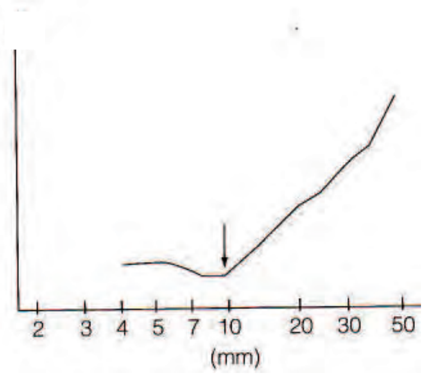


Figure 4
Curve showing 10 mm weathering depth on carved rock, Yungang grottoes.

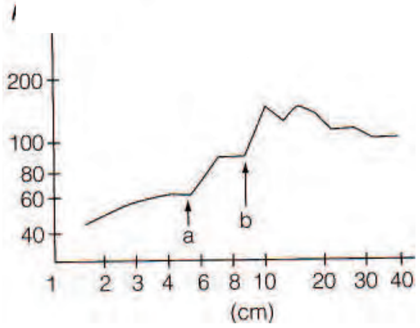


Figure 5
Curve determined on the Great Buddha statue at Leshan: a = depth of severely weathered zone; b = depth of weathered zone.

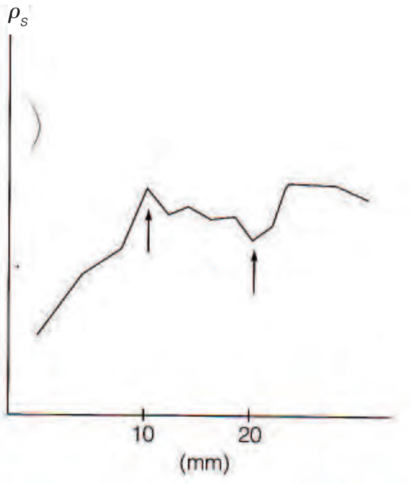


Figure 6
Measured curve at the Yungang grottoes. Severe salt accumulation occurs to a depth of 10 mm; exfoliation occurs at 20 mm.

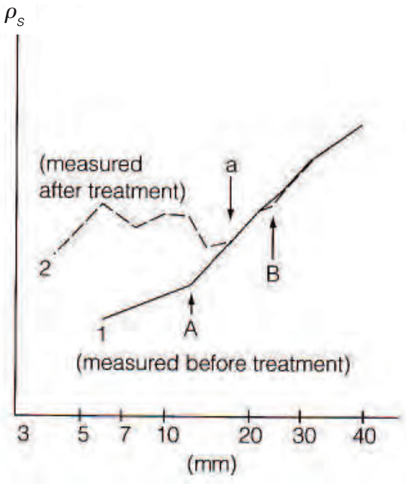


Figure 7
Effects of consolidants on resistivity curves: Curve 1, before consolidation; Curve 2 after consolidation.

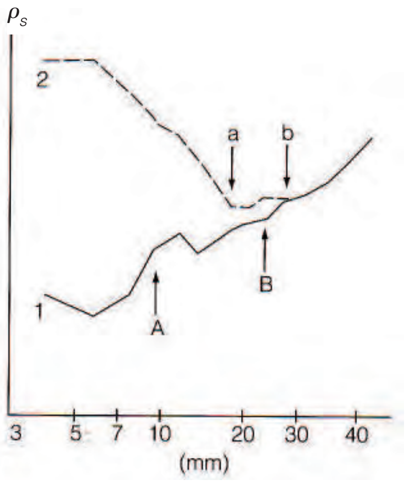


Figure 8
Effects of two different consolidants on resistivity.

cracking on the surface of the wall. These findings are consistent with the results of actual observations.

As stated previously, after consolidant has penetrated the surface of the rock and has solidified in it, resistivity is frequently increased. Organic materials, in particular, cause the resistivity to increase considerably. Therefore, the depth of penetration of the chemical agent can clearly be determined from the initial high resistivity on the measured curve and from a comparison of the same points on the curve before and after applying consolidant. Figures 7 and 8 show curves for the two determinations. Curve 1 in Figure 7 was determined before application of the consolidant, and Curve 2 was determined after its application. Curve 1 in Figure 7 reflects a weathering depth of 12 mm (A) and a less severe weathering depth of 24 mm (B). Curve 2 reflects penetration of the chemical agent (a) to a depth of 17 mm. In Figure 8, Curve 1 reflects a weathering depth of 10 mm (A) and a less severe weathering depth of 24 mm (B). Curve 2 reflects penetration of one chemical consolidant (a) to a depth of 17 mm and penetration of a different consolidant (b) to 28 mm.

Measurements on Test Blocks

Test blocks have relatively small volumes and can easily be moved and immersed in water. For this reason, the two-electrode arrangement method was used (Fig. 9). Three blocks were treated with different consolidants (Table 1). Determinations were made on various planes of the test blocks; specifically, the two electrodes A and M were arranged parallel to the surface, and the electrodes B and N were set at a distance. The test blocks were then submerged in water and the resistivity of the rock was determined at different depths. Because the test blocks were submerged in water, water permeated the weathered layers of the test blocks, lowering resistivity. On this basis, the depth of weathering was determined from the

Table 1 Test results using different consolidants

Consolidant	Thickness (mm) Weathered layers[a]			Penetration depth[b]	
	A layer	B layer	C layer	a layer	b layer
Potassium silicate (PS) No. 1[c]	12	24		17	
PS No. 2	12			6	
PS No. 3	10	28		14	
Methyltrimethoxysilane No. 1[d]	12	20		32	
Methyltrimethoxysilane No. 2	10	17		20	
Methyltrimethoxysilane No. 3	8	17		24	
Methyltrimethoxysilane No. 4	10			32	
Methyltrimethoxysilane No. 5	8	12		24	
PS and methyltrimethoxysilane No. 1[e]	10	20	38	20	38
PS and methyltrimethoxysilane No. 2	10	24		17	28
PS and methyltrimethoxysilane No. 3, test point 6	8	17		8	28
PS and methyltrimethoxysilane No. 3, test point 7	8	24		17	28
PS and methyltrimethoxysilane No. 4	8	14		20	28
PS and methyltrimethoxysilane No. 5	10	20		28	38
Methyltrimethoxysilane No. 1[f]	14	24		14	38
Methyltriethoxysilane	12	24		17	38

Notes

[a] A = severely weathered; B = moderately weathered; C = less weathered.

[b] Penetration depth of consolidants.

[c] Potassium silicate inorganic consolidants of different molar ratio (silica : potassium) and different concentrations in aqueous solution.

[d] Organic consolidants Nos. 1–5 are of different concentrations. [No further information was available from the authors with regard to the composition or method of application. Ed.]

[e] Organic consolidant was applied first, followed by the application of the inorganic consolidant.

[f] Methyltrimethoxysilane was applied first, followed by the application of the methyltriethyloxysilane.

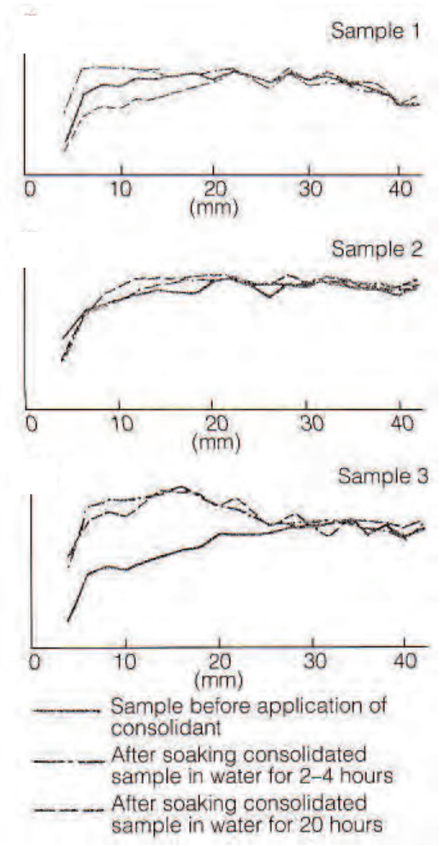


Figure 9
Resistivity curves for laboratory samples, showing consolidant penetration depth in millimeters.

measurement curve. For example, as shown in Figure 9, the depths of severe weathering of samples 1, 2, and 3 were 10 mm, 12–14 mm, and 10 mm, respectively, and the depths of moderate weathering were 12 mm, 20 mm, and 20 mm, respectively (Table 2). By comparing the differences in resistivity before and after the spraying with consolidation, the depth of penetration was determined.

Comparison of the differences in resistivity before and after application of a consolidation in the same test block, and after two hours and twenty hours of soaking, allows differentiation of the water-absorption capacity when different consolidants are being tested. Large quantities of

Table 2
Summary of data shown in Figure 9.

Sample	Resistivity method (mm)			Visual examination (mm)			Consolidant	Penetration
	A	B	C	A	B	C		
1	10–12		22	12		20–22	PS	good
2	12–14	20	28	14	22	24–26	PS and methyl-trimethoxysilane No. 3	poor
3	10	20	26	12	22	26	PS and methyl-trimethoxysilane No. 1	medium

A = depth of severe weathering.
B = depth of intermediate weathering.
C = penetration depth of consolidants.

water penetrate samples of high water permeability when they are soaked for long periods, causing resistivity to be lower than that of similar samples that absorb relatively little water when soaked for a short time.

However, the length of soaking does not have much effect on the resistivity of samples with poor permeability to water. For example, the resistivity shown in the first segment of the curve for sample 1 was greatly decreased after twenty hours of soaking, indicating that the sample was of good permeability. For sample 2, there was basically no change in resistivity as shown in the first segment of the curve after twenty hours of soaking, suggesting poor permeability. The permeability of sample 3 fell between that of the two other samples.

Conclusion

The resistivity method can be used to measure resistivity of rock surfaces at different depths of carved rock on tangent planes. For this reason, its use in determining the depths of weathering of rock sculpture and the depth of penetration of chemical consolidants applied to rock is feasible. Much of the data presented in this paper was compared with visual determinations and with measurements of drilling, and results confirmed that the method can satisfy the requirements of actual fieldwork. The equipment and measuring instruments developed were tested and used extensively in work on grottoes and carved rock. The resistivity method and the C-1 microdepth measuring instrument are also suitable for nondestructive measurements of the thicknesses of covering layers of concrete, lime, and argillaceous matter on rock and carved rock.

Investigations of the Deterioration and Conservation of the Dafosi Grotto

He Ling, Ma Tao, Rolf Snethlage, and Eberhard Wendler

This article describes part of an interdisciplinary, joint Chinese–German project on the preservation of the Dafosi grotto. It focuses on the properties of the sandstone, the influences of moisture and salts on the deterioration of the walls, and preliminary results on the conservation of the stone site. Aspects of Dafosi's art history, polychromy, stability, and rock mechanics are discussed elsewhere in this volume.

The following general description of the topography and geology of the area is based on the *80,000 Signs Report: The Study and Survey of the Environmental and Geological Situation and Deterioration of Dafosi Cave in Bin Xian* (1991). Dafosi is situated in the loess plain in the northern part of Shaanxi Province, near the city of Binxian. The landscape is characterized by the broad valley of the Jing River, which cuts into the yellow earth and the underlying red Cretaceous sandstones. The grotto itself is excavated into the red sandstone of the valley flanks (Fig. 1). The stone floor of the grotto is covered by flood sediments of approximately 2 m thickness, which have been produced by periodic flooding of the Jing River throughout its history.

The sandstone is overlaid by loess layers of the Quaternary period (early, middle, and late Q3). The geological profile shows a horizontal layering of the strata with 180 m vertical distance between the base of the valley and the top of the hill. The height of the sandstone rock is 55 m. Typical for sandstone in general, clay-stone layers of various thicknesses are interspersed between the sandstone rock series. These layers form impermeable barriers against the water that flows from the top of the hill along the fissures as well as through the rock itself.

One of these clay-stone layers intersects the Dafosi grotto about 2 m above the present ground level, with an intersection length of 65 m. The water that seeps out of this horizon layer trickles into the sediment layers covering the floor. This seepage water is the main source of deterioration of the statues and the walls inside the grotto. The sandstone is particularly damaged along the clay-stone horizon. Behind the Great Buddha in the grotto, the sandstone is eroded back to 2.5 m from its original surface.

Figure 1
View of the Dafosi grotto.

Weathering of the sandstone walls

The weathering of the sandstone walls inside the grotto can be divided into four vertical zones (Fig. 2), described as follows from bottom to top:

> Zone A (0–2 m): Thin sandstone layers separated by thin clay-stone layers. The sandstone is cracked into small blocks. The moisture content is high; there is little or no salt efflorescence. The top of Zone A is formed by a thick clay-stone layer. Nos. 1–3 drill-core and scraping samples are from this layer.

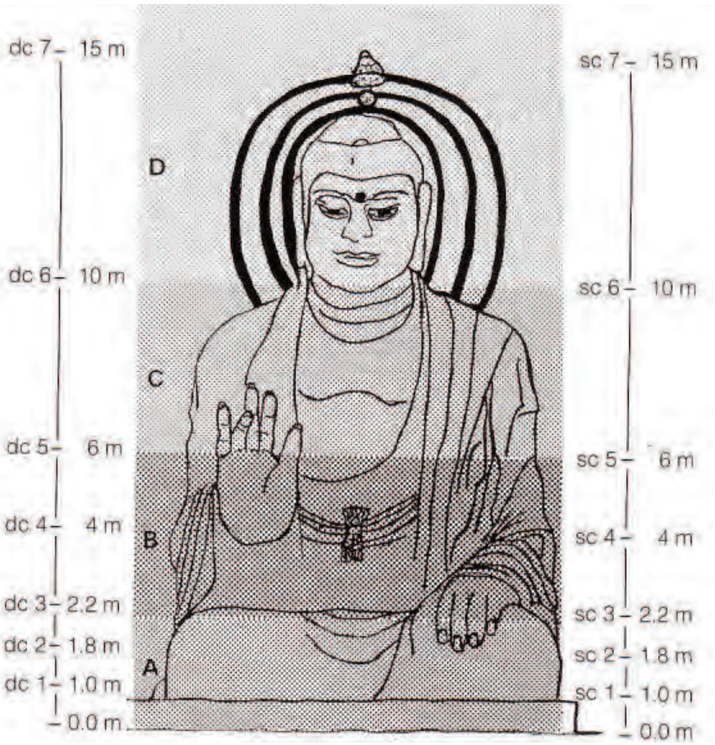


Figure 2
Schematic drawing of the Great Buddha and the locations of sampling: dc = drill core; sc = scraping sample from the surface. Shaded areas A–D show the level of deterioration, which is highest in Zone B, lowest in Zone D.

Zone B (2–6 m): Thick sandstone layers separated into large blocks. This zone is situated in the dynamic area of water migration and evaporation. Heavy erosion is evident at the clay-stone layer. Thick salt crusts and efflorescence can be found. Nos. 4 and 5 drill-core and scraping samples are from this layer.

Zone C (6–10 m): Thick sandstone layers separated by fissures. This zone is situated in the migration area of the most soluble salts and determines the upper limit of salt and moisture action. The moisture content is low, displaying little salt crusting or efflorescence. No. 6 drill-core and scraping samples are from this layer.

Zone D (10–23 m): Thick sandstone layers are separated by fissures. There is good ventilation. No salt crystallization is found. Remains of former wall paintings have been found in this area. No. 7 drill-core and scraping samples are from this layer.

The degree of deterioration is greatest in Zone B. To investigate the properties of the sandstone, samples were taken according to the stone varieties and the deterioration sequence at heights of 1, 2, 4, 6, 10, and 15 m. Two types of samples were taken: drill-core samples 2 cm in diameter and 30 cm in length taken from the wall at the left side of the Buddha, and scraping samples from the wall on the statue's right side. Eight soil samples were also taken to determine the salt content of the ground. Figure 2 shows the location of the drill-core and scraping samples.

Sandstone Types and Their Hydrological Properties

The following investigations were carried out to determine the physical and chemical properties of the stone types: microscopic thin-section analysis; measurement of density and of transport parameters of liquid water, water vapor, and moisture dilatation; and measurement of water-vapor absorption (sorption isotherm). The results are compiled in Table 1. Table 2 contains a comparison of selected properties before and after treatment with stone strengthener.

Table 1 Hygric properties of sandstones in Dafosi

No.	Height (m)	Rough density (g cm^{-3})	Porosity (vol. %)	H_2O (npr) (vol. %)	H_2O (vac) (vol. %)	W (kg m^{-2} h$^{-1/2}$)	B (cm h$^{-1/2}$)	W/B (kg m^{-3})	Vapor diffusion [μ (−)]	Hygric dilatation (μm m^{-1})
1	1	2.29	15.0	8.9	15.0	1.0	n.d.	n.d.	32	240
2	1.8	2.30	15.3	9.2	15.3	1.3	1.8	75	20	330
4	4	2.02	24.0	15.2	24.0	37	26	142	17	720
5	6	2.06	22.7	13.1	22.7	11	10	117	n.d.	400
6	10	1.91	28.5	18.0	28.5	36	24	158	13	520
7	15	1.96	26.7	17.1	26.7	20	14	142	14	370

Table 2 Properties of consolidated sandstones in Dafosi

No.	Height (m)	H_2O (npr) (vol. %)	W (kg m^{-2} $h^{-1/2}$)	Vapor diffusion [μ (−)]	Hygric dilatation (μm m^{-1})	Pull-off strength (N mm^{-2})
2	2	4.0 (9.1)	0.4 (1.3)	60 (20)	250 (320)	2.2 (1.9)
4	4	5.9 (15.2)	1.0 (37)	21 (17)	890 (720)	0.7 (0.5)
6	10	6.2 (13.1)	0.8 (11)	30 (19)	1000 (400)	0.9 (0.8)
7	15	5.5 (17.1)	0.7 (20)	33 (14)	320 (370)	0.8 (0.4)

Generally, the binding material of all the sandstone varieties studied is rich in clay and ferrous compounds, but the sandstones differ significantly below and above the clay-stone layer. Below the clay-stone horizon, the sandstones are matrix-rich, partly carbonate, and partly clay-rich; the grain size in this area is much smaller than in the upper zones. The sandstones above the clay-stone layer are grain-supported with a much greater visible porosity. The red color in this region is caused by ferric oxide clay layers coating the sand grains. Chlorite is the main clay mineral of the sandstones above the clay-stone layer, whereas illite and kaolinite prevail below it.

The moisture-transport properties of the sandstone indicates that the porosity of the sandstone increases with height, as shown in Table 1. The varieties below and above the clay-stone layer (at the top of Zone A) are very different in this respect. This behavior is expressed by the water-uptake coefficient W (kg m^{-2} $h^{-1/2}$) and the water-penetration coefficient B (cm $h^{-1/2}$). Both values were measured according to DIN 52617. The sandstone varieties in the upper part of the grotto show extremely high values of W and B. This explains the wide distribution of moisture and salts over the walls of the grotto. The dilatation (expansion of the stone when immersed in water, DIN 52450) was particularly enhanced in sample 4, located at a height of 4 m directly above the clay-stone layer. This maximum corresponds with the maximum salt content. It is known from many experiments that gypsum content significantly increases the dilatation of sandstone (Möller, Wendler, and Schuh 1992).

Water-vapor sorption isotherms (DIN 50008) at 20 °C were determined for six sandstone varieties. The isotherms shown in Figure 3 are of the same type and plot very close together. The absorbed water content increases continuously with increasing relative humidity. The sorption isotherms do not seem to be influenced by the salt content of the stone, however. This confirms the result that—besides gypsum and calcite, which are not hygroscopic—no other salts in major concentrations occur in the sandstone (Fig. 4).

The Distribution of Soluble Salts

Soil samples, drill cores, and surface-scraping samples were taken to identify the salts and their distribution in the grotto. Drill cores were sliced into sections to determine the depth distribution of the salts.

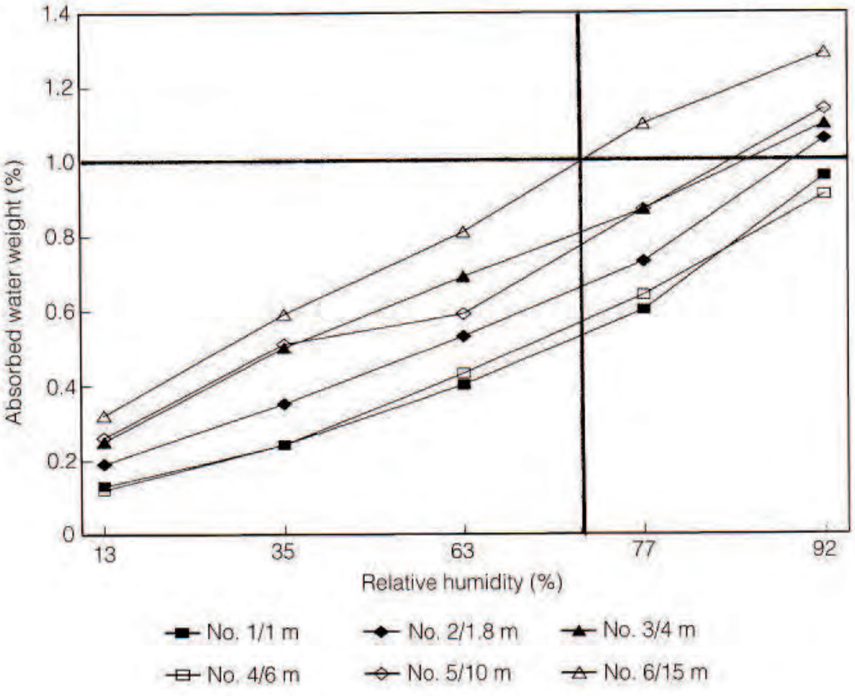


Figure 3
Water-vapor sorption isotherms (20 °C) of the sandstone types. LiCl = 12% RH; $MgCl_2$ = 35% RH; $NaNO_3$ = 65% RH; NaCl = 76% RH; KNO_3 = 93% RH.

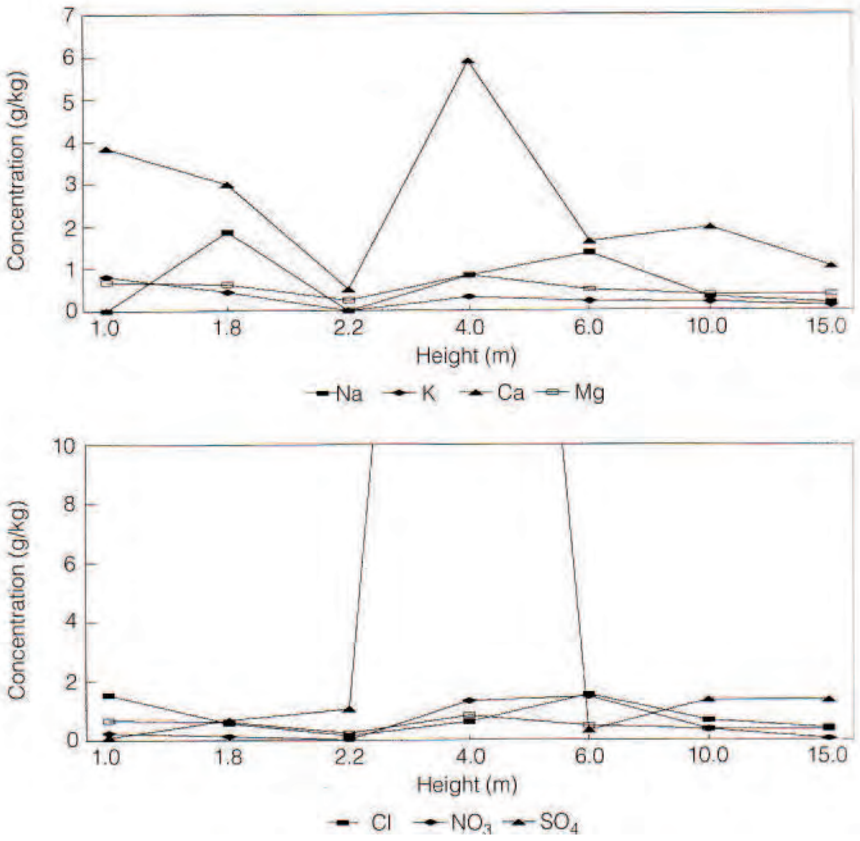


Figure 4
Vertical height profile of water soluble ionic species in the surface of the sandstone walls. Note the logarithmic scale in the anion's diagram.

In addition to river sediments, the floor of the grotto contains debris from the deterioration of the sandstone walls. The moisture content and salt content of the soil are quite high; the moisture content is 3–16 weight % with a mean of approximately 7–8 weight %. The principal

ions found are calcium and sulfate in a concentration of 5–10 g/kg. Nitrate and chloride are also present.

The vertical salt profile shows a characteristic zoning (Fig. 4). Salts are enriched in the zone between 2 and 6 m, which corresponds to the capillary rise of moisture above the clay-stone layer. The increase in calcium below that layer can be explained by the influence of water seepage from that region. From 6 to 15 m below that layer, the content of soluble salts is almost constant. The distribution of salts coincides with the extent of damage to the sandstone walls, as illustrated in Figure 2.

The total ionic content found in the sandstone is not very different from that of the soil samples. Calcium and sulfate (gypsum) are the main ions. Nitrate is slightly more enriched in the soil samples than in the drill-core samples. The balance of the total ionic species soluble in water further indicates the presence of sodium and magnesium salts.

Salt efflorescence collected in the grotto was analyzed by X-ray diffraction and found to consist of gypsum and calcite. The same salts also crystallized from the eluates used to determine the anion and cation profiles. The presence of gypsum can be explained by the reaction of dissolved calcium hydrogen carbonate with sulfate-containing rainwater and groundwater. Because the loess contains large amounts of calcite, which is dissolved by rainwater, this result clearly demonstrates that both of these salts are transported by the water seeping from the top of the hill through the sandstone rock.

Depth profiles of water-soluble ionic species were analyzed to determine the distribution of salts in the interior of the sandstone. The profiles are typical for the prevailing climatic conditions. Near the ground, where there is little evaporation, a homogeneous depth distribution is found. At a height of 4 m, in the dynamic zone of wetting-drying cycles, the salts are enriched on the surface of the sandstone. The salt content decreases significantly with increasing height.

The salt content in the rock is low to medium compared to the total porosity of the sandstone, which is in the order of 25 volume %. The main salts found, gypsum and calcite, are not hygroscopic. Therefore, the moisture content in the stone is caused by seeping rainwater and moisture condensation due to the climatic conditions.

Climatic Measurements

Measurements carried out since 1992 show that the daily variations of temperature and relative humidity directly outside the grotto are buffered inside. Near the ground, the temperature is always very close to that of the dew point, so condensation conditions prevail. With increasing height, ventilation and drying conditions improve; consequently, inside and outside temperatures and relative humidity levels are similar. On the basis of mean monthly data, the dew-point interval (the difference between air temperature and dew-point temperature) was calculated inside the grotto (Fig. 5). Results show that the interval between the inside temperature and the dew point is less in the spring and summer and more during the autumn and winter months. The latter period can, therefore, provide good drying conditions with better possibilities for conservation measures.

Stone Consolidation

Until now, only a few experiments have been carried out with original Dafosi material (Table 2). The treatment with Stone Strengthener Wacker OH (tetraethoxysilane) causes some evident changes of stone properties: the water uptake coefficient is lowered, as is the water uptake under normal pressure. This result can be explained by the deposition of SiO_2 gel in the pore space, which remains hydrophobic for some weeks after the treatment. Corresponding to that result, the water-vapor-diffusion resistance number is increased. Dilatation is also increased, though only slightly. Because of the size of the samples available, only the pull-off strength according to DIN 18555, part 6 could be measured; the results showed a clear increase. Future experiments will be undertaken to develop an adapted stone-consolidation program using Wacker OH and formulations containing diethoxy-dimethylsilane (DEX-DMS) as a plasticizer for the SiO_4 tetrahedral network.

Suggestions for Further Research and Intervention

Origin of the seepage water

Using the porosity and capillarity data measured, the transport paths of the seepage water can be approximated. Microscopic thin-section analysis shows the size of the macropores of the sandstone above the clay-stone layer to be ±0.1 mm. Using this figure, the height of capillary rise of water in these pores can be calculated as approximately 0.2 m. When the water column in the stone is longer than approximately 0.2 m, however, the pore water migrates downward and trickles out of the pore system. The rocks of the upper series in the Dafosi grotto can, therefore, be classified as good moisture conductors (*80,000 Signs Report* 1991). Rainwater is quickly conducted downward through the massive rock sequences. Then the water seeps out along fissures, and most of it is transported along these paths. Finally, all migrating water collects at the clay-stone layer. These different transport paths probably cause the water to originate from an extensive area on top of the hill. Therefore, the installation of a geotextile (water-impermeable membrane) to control the seepage does not appear to be practical.

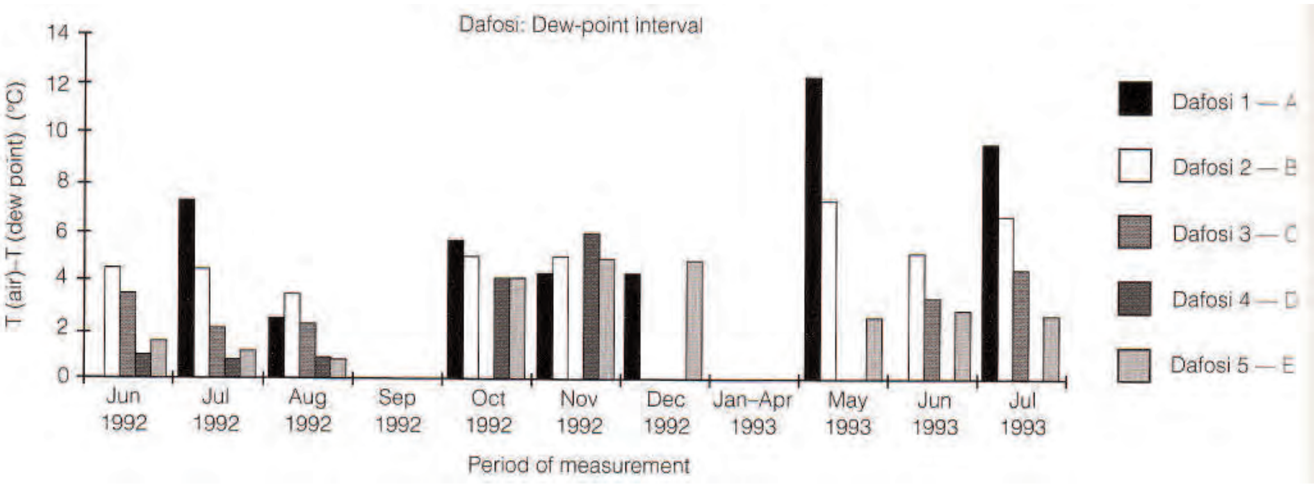


Figure 5
Air temperature–dew-point temperature interval at different levels in the grotto. Location of the records: Dafosi 1 = outside air in front of the grotto; Dafosi 2 = 10 m; Dafosi 3 = 8 m; Dafosi 4 = 2 m behind the Buddha; Dafosi 5 = 0 m, on the floor.

Reducing moisture in the grotto

The primary challenge to preventing further deterioration of the site will be to lower the humidity inside the grotto by diverting water seepage. For this purpose, the eroded space along the clay-stone layer will be closed by a wall, and the water that collects behind the wall can then be drained by tubes. As an additional measure, sediments covering the grotto floor will be removed as a means of increasing the evaporation area and lowering the salt contamination of the grotto as a whole.

Stone conservation in the grotto

Although the damage observed is extensive, the following factors may facilitate the conservation of the sandstone: The main salts present are gypsum and calcite; since these salts are not hygroscopic, they do not contribute to an increase in the moisture content of the stone. The salt content is moderate to medium compared to the total porosity of the stone, and the salts are concentrated in the outer 5–10 mm. Sacrificial mortar layers are able to displace the evaporation zone, simultaneously displacing the accumulation of salts from the stone surface into the rendering. With time, some extraction of the present salts can be expected, although gypsum and calcite are quite insoluble.

Because neither gypsum nor calcite are hygroscopic, the moisture of the stone is determined primarily by the amount of seeping water and condensation from the air. Sorption isotherms, therefore, give an indication of the appropriate conditions for conservation. Figure 3 shows that when the relative humidity is below 75%, the amount of absorbed water is less than 1 weight %, which is low enough to obtain a sufficient penetration depth of stone consolidants. For this reason, it is absolutely necessary to monitor the climate in the grotto and wait for these appropriate conditions. Yet treatments can be carried out only after a long dry period. Karsten pipe measurements can help determine whether uptake-and-penetration depth of a stone consolidant is sufficient (Wendler and Snethlage 1989).

In the near future, conditions appropriate for the application of a stone consolidant can be expected for only the upper parts of the grotto. The treatment, therefore, will be carried out in two or three steps. The upper areas, which are already sufficiently dry, will be treated first. Then, after the removal of the floor sediments and the control of the seeping water with drainage tubes, the lower walls will be allowed to dry out for several years. When dry, the remaining areas of the grotto can also be treated.

Acknowledgments

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Color Change of Pigments in the Mogao Grottoes of Dunhuang

Nobuaki Kuchitsu, Duan Xiuye, Chie Sano, Guo Hong, and Li Jun

As is typical of old mural paintings, the art in the Mogao grottoes of Dunhuang has undergone discoloration or color change. A dark brown material has been observed in many paintings, particularly in portrayals of human skin. In some cases, the skin looks black. These dark colors are thought not to be the original colors applied to the wall. Art historians note that, as the Mogao grottoes are located in northwest China, the skin was likely to have been originally painted in yellow. Color change is therefore suspected. It is well known that local people lived in some of the cave temples, as evidenced by soot deposits on the wall paintings, but this is different from the darkening of specific parts of paintings. Accordingly, it is important to analyze the mineral pigments believed to have undergone color change to determine the original colors and to prevent further alteration in the future.

Previous Work

The color change of pigments in the Mogao grottoes has been studied by Duan and coworkers (e.g., Duan 1987; Duan et al. 1987) and Li (1992). They noted that minium (Pb_3O_4) sometimes changes into plattnerite (PbO_2) (i.e., orange changes into black) on some mural paintings. Substantial microscopic observation of a dark brown sample from the painting of human skin in Cave 205 (Tang dynasty) revealed that it is divided into two layers: a thin surface black layer and the dominant inner orange layer. The black layer corresponds to plattnerite, and the orange layer corresponds to minium. The original depiction of human skin had surely been painted a cream color, where orange was added to an initial white coat, but oxidation of minium into plattnerite changed the color to dark brown. This transformation is important not only to art historians but also to conservators of wall paintings. Because oxidation is not the only threat to pigments, it is necessary to analyze and describe the many cases of color change of pigments.

Samples

Cave 194 was surveyed for color change. This cave temple was excavated in the Tang dynasty and partially repainted in the Xixia dynasty. At least five

colors present in the wall paintings are recognizable and have not suffered significant color change: red, green, yellow, black, and blue. Dark brown parts distinguishable from soot are also present. Though the paintings have been severely damaged by salt crystallization, the pigments themselves appear hardly changed, except for the dark brown areas. Sampling of the pigments in this grotto was conducted at two points on the south wall of the main chamber. The dark brown and green pigments are the focus of the following observations.

Methods

After samples were embedded in resin, a cross section was observed under a high-powered microscope. Chemical analyses were conducted using a JEOL JSM-840A with JEOL JXA-840A electron probe microanalyzer (EPMA). Measuring conditions were 15 kV and 1×10^{-8} mA. Mineralogical analyses were also undertaken through examination by X-ray diffraction (XRD) using a JEOL-3500-DX-MAP2 instrument. The measuring conditions were 30 kV and 400 mA, and the diameter of the microbeam was 100 μm. Both copper and chromium were used as the radiation sources.

Results

Dark brown sample

EPMA data are shown in Figure 1a–c. Microscopic observation of the cross section of the dark brown sample revealed that it is composed of two parts: the main part, which is red; and a very thin surface layer, which is black (Fig. 1a). The distribution of iron concurs with the pigment layer (Fig. 1b). The distribution of sulfur concurs with the outer margin of the pigment layer, which corresponds to the black surface layer (Fig. 1c). XRD data are shown in Figure 2. Pyrite (FeS_2) and hematite (Fe_2O_3) have also been identified as components of the sample, a result that is consistent with the EPMA data.

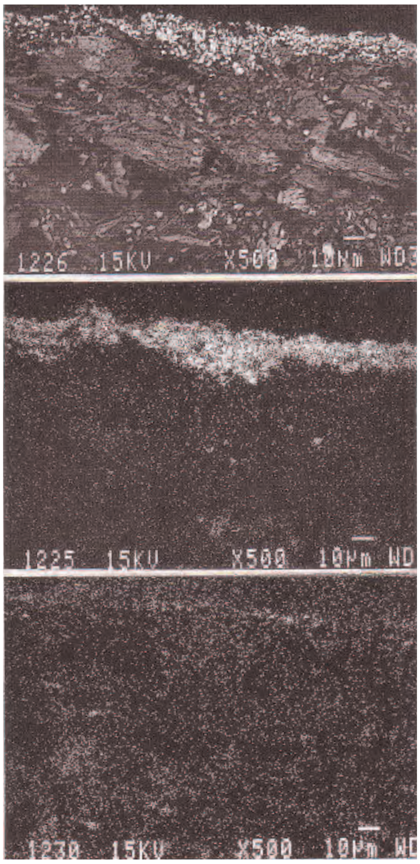
Green sample

Examination of the cross section shows that the green pigments have been partially dissolved into the embedding resin, leaving them bluish and rather ambiguous. The pigment layer, however, is still recognizable. EPMA data for the green sample are shown in Figure 3. The distribution of chlorine agrees with that of copper, which corresponds to the pigment layer. Moreover, the distribution of sulfur also agrees with that of copper. XRD analyses show that the green sample is composed mainly of atacamite, $Cu_2Cl(OH)_3$, with minor amounts of antlerite, $Cu_3SO_4(OH)_4$, consistent with the EPMA data.

Discussion

Although hematite is common as a red pigment, pyrite is not. Therefore, it is thought that the dark brown sample was originally red and composed of hematite. The subsequent formation of the black surface layer, composed of pyrite, caused the color to change to dark brown. If this is indeed the

Figure 1a–c
Elemental distribution map of the cross section of dark brown pigment in Cave 194 by EPMA, in which (a) the bright part corresponds to heavy elements, the dark part corresponds to light elements, and the bright band is presumed to be the pigment layer. The other images show (b) distribution of iron, agreeing with the presumed pigment layer, which is seen as the bright band; and (c) distribution of sulfur, agreeing with the outer margin of the pigment layer.



a

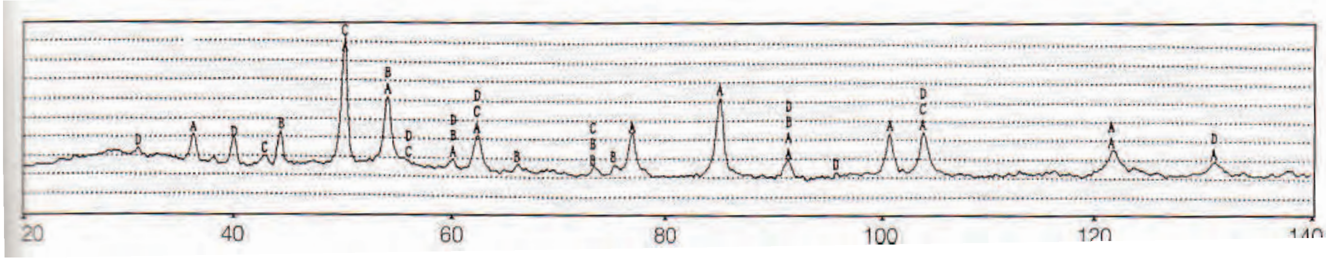
b

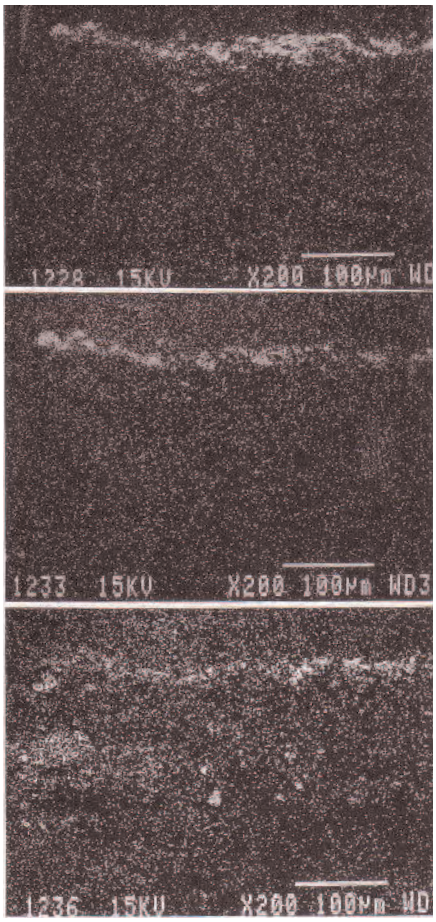
c

case, then the cause of this color change can be attributed to the transformation of hematite into pyrite through its interaction with a sulfur-containing compound. It is notable that hematite, which is generally regarded as much more stable than minium, is also subject to change.

Generally, the green pigments in the mural paintings of the Mogao grottoes are regarded as stable because little color change is detectable with the naked eye. However, the green samples of Cave 194 show that there has been some dissolution of the green pigment into resin. This suggests the occurrence of a mineralogical change. Although atacamite is a mineral commonly present in green pigment, antlerite—which is barely distinguishable from atacamite with the naked eye and may be an alteration product of atacamite—may be present. Antlerite is soluble in water. Thus, the green pigments of Cave 194 require consideration of their preservation needs. Consequently, color change is not the only threat to the conservation of mural paintings; mineralogical alteration should

Figure 2
X-ray diffraction data of the dark brown pigment in Cave 194. The radiation source is chromium. Peaks labeled A show the existence of hematite (Fe_2O_3); B peaks show the existence of calcite ($CaCO_3$); C peaks show the existence of pyrite (FeS_2); D peaks show the existence of quartz (SiO_2). Calcite and quartz are commonly observed in the ground layer of mural paintings. Hematite and pyrite are identified as the main components of the pigment layer.





a
b
c

Figure 3a–c
Elemental distribution map of the cross section of green pigment in Cave 194, in which (a) the distribution of copper corresponds to the pigment layer; (b) the distribution of chlorine is consistent with the distribution of copper; and (c) the distribution of sulfur also agrees with the distribution of copper.

also be considered, and it is necessary to understand the precise condition of the pigments when considering the preservation of mural paintings.

In both cases, sulfur plays an important role in the deterioration of pigments. The origin of the sulfur has not yet been ascertained. Its distribution in the cross section suggests that it did not come from the geological strata into which the grottoes are excavated. Because sulfur is found only on the outer part of the pigment layer, it is believed that this element is present in the atmosphere of the cave. It is therefore necessary to determine the atmospheric environment of the Mogao grottoes. While this study has not yet detected significant air pollution in Cave 194, continuous observation is needed.

Conclusion

In Cave 194, the alteration of hematite into pyrite was observed as the cause of a color change from red to dark brown. Although green pigments such as atacamite are regarded as stable, they, too, are subject to alteration. This process does not necessarily cause color change as with the conversion of atacamite into antlerite; nevertheless, the alteration could possibly pose a threat to the conservation of mural paintings. Because sulfur plays an important role in the deterioration of pigments, it is necessary to study how it enters the grotto in order to prevent its contact with the mural paintings.

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Analysis of Wall Painting Fragments from the Mogao and the Bingling Temple Grottoes

Ian N. M. Wainwright, Elizabeth A. Moffatt, P. Jane Sirois, and Gregory S. Young

In 1988, the Analytical Research Laboratory of the Canadian Conservation Institute, in collaboration with Li Zuixiong of the Dunhuang Academy, undertook the analysis of wall painting fragments from the Mogao grottoes at Dunhuang and the Bingling Temple grottoes near Lanzhou, Gansu Province. A total of thirteen fragments—ten from the Mogao grottoes and three from the Bingling Temple grottoes—were studied. Their precise locations within the caves are not reported here; the fragments were chosen to be representative of the range of colors observed, including white, black, red, blue, beige, green, and purple. The investigation had several objectives, including an examination of the clay and paper supports, characterization of the binding medium of the paint and its deterioration, and analysis of pigments and other inorganic materials. In addition to the thirteen fragments examined, a comparative analysis was undertaken of several raw materials of both plant and animal origin—including fish, bone, and skin glues, and peach pitch. The authors further undertook a review of literature pertaining to the materials of Chinese wall paintings to evaluate processes of site deterioration. The aim was also to share the analytical methods with the Dunhuang Academy for the development of its conservation science program.

A number of studies of pigments and other materials relevant to these analyses have been reported, notably work by Gettens (1938a, 1938b) on Chinese wall paintings including those of Dunhuang (see also Warner 1938), by Delbourgo (1980) on a ninth-century silk painting from Dunhuang, and by Warner at the British Museum, whose results are described in *Buddhist Cave Paintings at Tun-Huang* (Grey 1959). Two unpublished reports by Gettens (1935, 1936), which include experiments on the alteration and discoloration of red lead, are on file at the Fogg Museum of Art in Cambridge, Massachusetts. The authors' laboratory has published results on three wall paintings from the Royal Ontario Museum in Toronto (Moffatt, Adair, and Young 1985), in which calcium oxalates were found. Winter (1984) provides a bibliography on pigments in China, which was invaluable to our research. A review of the causes of deterioration of the Mogao grotto paintings is given by Qi Yingtao (1984).

A parallel project was undertaken at the Dunhuang Cultural Relic Research Institution and published by Hsu Wei-yeh, Chou Kuo-hsia, and Li Yun-ho in *Dunhuang Yanjiu* (1983). Their study was based on the analysis of 293 samples from the Mogao grottoes and showed that the following pigments were used: kaolin, calcium carbonate, lead chloride, lead sulfate, lead chloride carbonate, lead carbonate, quartz, red ocher, hematite, cinnabar, red lead, realgar, azurite, lapis lazuli (including synthetic ultramarine), malachite and copper chloride, graphite, ferric sulfate, gold powder or gold leaf, and mica. The discoloration of red lead and the nature and genesis of copper chlorides in the greens are also discussed.

Methods of Analysis

Cross sections were prepared by embedding fragments in a polyester casting resin and grinding one transverse face, using silicon carbide papers, followed by polishing with alumina on a synthetic velvet lap. Because of the friable and porous nature of the fragments, the embedding plastic was introduced with vacuum impregnation. Sections were examined by polarized light, incident light, and fluorescence microscopy,[1] and by X-ray microanalysis using a scanning electron microscope equipped with secondary and backscattered electron detectors and an X-ray spectrometer.[2]

Debye-Scherrer X-ray diffraction and diffractometry were used to identify the inorganic pigments used. Samples of pigment were mounted on glass fibers using silicone grease and then mounted in Gandolfi cameras. Clay used for preparing the sandstone walls for painting was studied by X-ray diffractometry to determine the major clay mineral constituents present.[3]

The organic component of the paints (i.e., the vehicle or binding medium) was studied by Fourier transform infrared spectroscopy with samples mounted in a high-pressure diamond anvil microsample cell.[4] Difficulties often encountered with this kind of analysis include very low concentrations of organic materials (e.g., less than 3–5%) and interferences in the infrared spectra. Because of the low concentrations encountered, chromatographic separation methods, such as thin-layer chromatography, were not pursued. An attempt was made to detect the presence of an organic vehicle in the pigment and preparation layers by using microscopical stains and fluorescence microscopy. Two fluorescent stains, fluorescein isothiocyanate and Rhodamine B, were used following the method of Wolbers and Landrey (1987). The first was dissolved in absolute ethanol (0.125 g in 50 ml). The second was dissolved in analytical-grade acetone at the same concentration. Samples were placed on microscope glass slides, and a drop of one of the stains was applied. After the solvent had evaporated and the stained sample dried, as indicated by a color change, a coverslip was applied. Mineral spirits was introduced under the coverslip by capillary action, and samples were studied by fluorescence microscopy. An aqueous, fluorescent stain, Fungi-Fluor, was used to detect the presence of fungal infestations in the paint layers.

Results

The cross sections generally revealed a rather simple sequence, with thin paint layers applied to a preparation layer on top of the original clay supporting surface. The clay support consisted of a heterogeneous aggregate of particles showing a wide range of shape and size. Voids, cracks, and other discontinuities were frequently observed in the support. Cleavage within the support was also quite common. Straw was identified in the clay underlayer of all fragments. The distribution of straw in the clay varied from separate individual fibers to coarse bundles. Paper samples observed in some fragments were processed straw fibers. Pigment layers were loose aggregates with often very poor adhesion.

White layers from the Mogao grottoes were composed primarily of calcite and talc with traces of calcium oxalates and quartz. Lead sulfate was also found. Black surface layers contained quartz, calcium oxalates, a trace of calcite, and possibly a trace of talc. Red layers were composed of hematite, quartz, calcite, and calcium oxalates. Black and red pigments could not be identified in all cases. Azurite, and possibly atacamite or paratacamite, was observed in blue layers. Greens at Bingling included botallackite, $CuCl_2 \cdot 3Cu(OH)_2 \cdot 3H_2O$, and possibly atacamite or paratacamite, $Cu_2(OH)_3Cl$, or a copper chloride hydroxide hydrate, $Cu_7Cl_4(OH)_{10} \cdot H_2O$. A gold-colored layer consisted of an alloy of gold and silver. Minium (red lead), Pb_3O_4, was also identified as a pigment at both the Mogao grottoes and the Bingling Temple grottoes, partially converted to reddish-brown or black plattnerite, PbO_2. Calcium carbonate (calcite) was observed in the preparation layer between the clay substrate and the pigment layers. It was also found as an additive to the clay support.

With two possible exceptions, no binding medium was detected by infrared spectroscopy in the samples from either the Mogao or Bingling Temple grottoes. The exceptions were the detection of trace amounts of organic material in a red surface layer from one fragment and in a black layer from another that could not, however, be attributed to a specific material. Attempts to isolate the organic material from the red layer for spectroscopic identification were unsuccessful. Similarly, no binding medium could be detected in the pigment layers using the microscopical staining method. This indicates that if there is a residual medium, it is present at a very low concentration. This is consistent with the observation of poor adhesion of pigments observed in the cross sections.

Calcium oxalates were detected in varying concentrations and were not restricted to any particular colors as they were identified in samples of white, black, red, green, and light blue paint. No appreciable concentration of oxalates was present in the clay layer under the pigmented surface layer, and no oxalates were detected in a fragment from a small building at the Mogao grottoes. Copper oxalate appeared to be present, along with botallackite, in the green samples from two fragments; however, the presence of calcium and copper oxalates was not confirmed by X-ray diffraction. The presence of calcium oxalates was usually determined from the infrared spectra. It is not possible to distinguish which hydrates of calcium oxalate were present by infrared spectroscopy.

Calcium oxalate exists in a number of hydration states, primarily weddellite ($CaC_2O_4 \cdot 2H_2O$), and whewellite ($CaC_2O_4 \cdot H_2O$) with other hydrated forms up to $CaC_2O_4 \cdot 3H_2O$. The copper oxalate may be the reaction product of a copper-containing pigment and oxalic acid.

The mechanism of incorporation of the oxalates into the paint layer has not been determined, but a number of possibilities exist (Moffatt, Adair, and Young 1985:234–38; Wiedemann and Bayer 1989:127–35). Calcium oxalates may have been present in the paint layer as an original constituent. They may have resulted from a treatment of the surface with oxalic acid, which subsequently reacted with calcite—present in the matrix—to form calcium oxalate. The origin of oxalates from the use of oxalic acid for cleaning and protective or aesthetic treatments has been the subject of speculation (Saiz-Jimenez 1989: 127–35; Moffatt, Adair, and Young 1985:234–38; Agrawal et al. 1987:447–52). Alternatively, the oxalates may be of microbiological origin. The formation of oxalates by microorganisms, such as lichens and fungi, is well documented (Saiz-Jimenez 1989:127–35). These oxalates, usually whewellite and weddellite, are produced by the reaction of calcium carbonate with the oxalic acid produced by lichens. No stained, fluorescent fungal hyphae were evident in any of the samples. Cellular debris of processed straw was observed in some of the paint layers, mainly pieces of parenchymatous cells, some whole cells, and segments of fibers. From the small amount of sample material investigated, no correlation could be shown between the presence of straw and the presence of calcium oxalate. Because many plants, including straw, produce quantities of oxalates, further study should be undertaken to determine if such a correlation exists.

Plattnerite (PbO_2) was observed in some samples. The mechanism of discoloration of red lead and its conversion to plattnerite has been discussed by West FitzHugh (1986:109–39) and by Petushkova and Lyalikova (1986:65–69) and was the subject of an unpublished investigation by Gettens (1935, 1936). It cannot be stated whether the transformation results from exposure to light, microbiological activity, or the presence of water or carbon dioxide.

Discussion

The typical structure of a wall painting at the Mogao or Bingling Temple grottoes begins with a supporting layer of clay, sometimes mixed with calcium carbonate, which was applied to the sandstone grotto wall to obtain a more even surface for working. A preparation layer consisting of clay and straw with calcium carbonate (e.g., chalk, whiting, lime white) was applied next, prior to the execution of the design surface itself. Materials, such as various clay minerals, insoluble salts, proteinaceous adhesives, and so on, react in moist or humid environments in ways that are damaging to painted surfaces. Clays form an integral part of the structure and fabrication of the wall paintings. Diurnal or seasonal variation in temperature and relative humidity within the grottoes can be expected to cause anisotropic expansion and contraction of clays with respect to the

sandstone wall and the paint (pigment) layers. It can be expected that this will result in a loss of adhesion within the clay layers and between the preparation layer and the pigments. The cross sections showed that cleavage and exfoliation are indeed occurring in these areas.

The colored pigments identified in this study were hematite, azurite, minium (red lead), and a number of copper compounds, including possible identifications of atacamite or paratacamite and a copper chloride hydroxide hydrate. The original black pigment was not positively identified but is most probably a bone black and not, for example, a charcoal black. The black mineral plattnerite, a conversion product of red lead, was also observed. The gold layer in one sample was an alloy of gold and silver. Because of the thin application of paint, it was frequently difficult to determine if white or translucent materials were intentional fillers or extenders of the paint or if they were part of the substrate or preparation layer. Such compounds included quartz, calcite, gypsum, talc, and possibly muscovite.

The absence of typical levels of binding medium found in paints in other cultural contexts, as well as the presence of calcium oxalates and the presence of plattnerite, suggest that the paintings have been subject to a complex process of deterioration that may include one or more microbiological processes. No evidence was found to allow a categorical statement of what precise environmental agent or agents were responsible for the occurrence of plattnerite or calcium oxalates.

Acknowledgments

The project summarized in this paper was undertaken at the Canadian Conservation Institute (CCI) in collaboration with Li Zuixiong of the Dunhuang Academy. The authors wish to thank the following for their advice and assistance in obtaining literature references: W. T. ("Tom") Chase, Technical Laboratory, Arthur M. Sackler Gallery, Freer Gallery of Art, Smithsonian Institution; Elisabeth West FitzHugh and John Winter, Freer Gallery of Art, Smithsonian Institution; the Center for Conservation and Technical Studies, Harvard University Art Museums; Maureen Clark, Library, Canadian Conservation Institute. The interest of Charles Gruchy, Director-General, Canadian Conservation Institute, who was instrumental in establishing a collaborative project between the CCI and the Dunhuang Academy, is gratefully acknowledged, as is the support of John Taylor and the late Kenneth Macleod.

Notes

1 A Leitz (Wetzlar) vertical fluorescence illuminator (after J. S. Ploem) was used on a Leitz Orthoplan microscope with a high-pressure mercury vapor lamp. It permits a selection of exciter filters that correspond to the ultraviolet, violet, blue, and green regions of the spectrum. Dichroic beam-splitting mirrors and matched barrier filters permit selection of the appropriate visible light fluorescence.

2 A Hitachi S-530 scanning electron microscope with a Tracor X-ray Microtrace Hypersense lithium-drifted silicon X-ray detector was used with a Tracor Northern TN-2010 spectrometer. Using this technique, chemical elements of an atomic number greater than or equal to 11 (sodium) present in the sample can be identified with a sensitivity of about 1%.

3 A Philips PW 1130 X-ray generator and a cobalt tube (with an iron beta filter to eliminate the cobalt K_β line) was used with a 114.6 mm diameter Debye-Scherrer X-ray diffraction camera and Gandolfi mechanism for small particulate samples and fragments. Samples were irradiated with cobalt K_α radiation, and patterns are recorded on CEA 25 film. Larger samples were analyzed with a Philips PW 1050/76 diffractometer (goniometer).

4 A Nicolet 5DX FTIR spectrometer was used in this study. For further information on the diamond anvil microsample cell, see Laver and Williams (1978:34–39).

Materials and Suppliers

Fluorescein isothiocyanate and **Rhodamine B** were obtained from Sigma Chemical Company, P.O. Box 14508, St. Louis, MO 63178.

Fungi-Fluor was obtained from Polysciences, Inc., 400-T Valley Road, Warrington, PA 18976-2590.

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Color Measurement at the Mogao Grottoes

Michael R. Schilling, Li Jun, Li Tie Chao, Guo Hong, Li Zuixiong, and Duan Xu Xe

In 1989, a long-term project of monitoring, documentation, preservation, and training was initiated at the Mogao grottoes by the Getty Conservation Institute in collaboration with the State Bureau of Cultural Relics of the People's Republic of China and the Dunhuang Academy. An important aspect of the project was the study of the colors and appearance of the wall paintings and statues in the grottoes. Selected members of the staff of the Dunhuang Academy were instructed in the fundamentals of color measurement, the use of the instrumentation, normal operating procedures, and final data interpretation with the aim of establishing an ongoing program of color measurement at the Mogao grottoes (Schilling 1989). The following is a summary of the theory and practice of color measurement and its usefulness to the project.

Rationale for Color Documentation

Color documentation is an integral component of the project for a number of reasons. The primary purpose is to provide a stable record of the present appearance of the colors of the wall paintings at the inception of the project. Many factors can alter the appearance of the paintings' colors, such as physical aging or the methods used to preserve the paintings. To monitor the stability of the painted surfaces, it is imperative to have a record of the colors as they appear prior to treatment.

Color documentation is also important in laboratory experiments conducted at the Dunhuang Academy that are designed to study the darkening of red lead and other pigments when exposed to bright light and known relative humidity (Schilling 1989). The extent of color change can be quantified through the use of a numeric system of color expression.

Techniques for Documenting Color

Documentation of color can be accomplished by one of several methods. Color photography, the technique most frequently used in conservation, is an effective tool for quickly documenting the color and condition of objects. However, the value of the photographic record is severely limited

by the inaccuracy of color rendering and the impermanence of the dye layers and support.

A set of colored reference chips categorized by hue, value, and chroma (HVC) is the basis of the Munsell system of color notation. To describe an object's color with the Munsell system, the chip closest in color to the object is located and the HVC data on the chip noted. The quality of the color match strongly depends on lighting conditions and the color acuity of the observer (Billmeyer and Saltzman 1981).

Measuring devices, such as spectrophotometers and tristimulus colorimeters, offer another means of documenting color. These instruments provide a numeric expression of color that is based on mathematical conversions of tristimulus values. Numeric color records are inherently more accurate, precise, and stable than records obtained from other methods; therefore, they are preferred in conservation (Billmeyer and Saltzman 1981).

A Minolta Chroma Meter CR-121 was the instrument chosen to record the color data at the Mogao grottoes. The instrument is a portable, battery-operated, tristimulus colorimeter ideally suited for field projects and museum studies (Schilling 1993a, 1993b, 1993c). The measuring head has an aperture 3 mm in diameter and houses a built-in xenon flash. A small piece of Gore-Tex was applied to the end of the instrument to prevent damage to the wall paintings during measurement. The instrument was calibrated against a white ceramic tile prior to use.

CIELAB Color Notation

One of the most common numeric systems for expressing color or color difference is CIELAB notation, which utilizes the principle of opposing colors (Billmeyer and Saltzman 1981). Lightness is defined as L^*, and hue is expressed in terms of a^* and b^*. Positive values of a^* refer to red hues, and negative values to green hues. Similarly, yellows have positive b^* values, and blues have negative values. Color data may be expressed graphically or in tabular form. Color charts, which are graphs of b^* versus a^*, or L^* versus a^*, are convenient for illustrating groups of color measurement data and for providing visual alternatives to data tables. Figure 1 illustrates some of the main features of the system.

Instrument Evaluation

An important component of any color monitoring program is the evaluation of the performance of the color-measuring device. In measurements of color difference, absolute accuracy is desirable but not critical. It is far more important that the measuring device be stable over the time period involved. Otherwise, any apparent color change would be indistinguishable from instrumental drift. Also, measurement reproducibility is also greatly affected by surface uniformity, which is significant, as the surfaces of wall paintings tend to be quite irregular.

Thus, the instrumental accuracy, stability, and reproducibility of the Minolta Chroma Meter CR-121 were evaluated to assess the effects of each on the measurement data. In measurements of British Ceramic

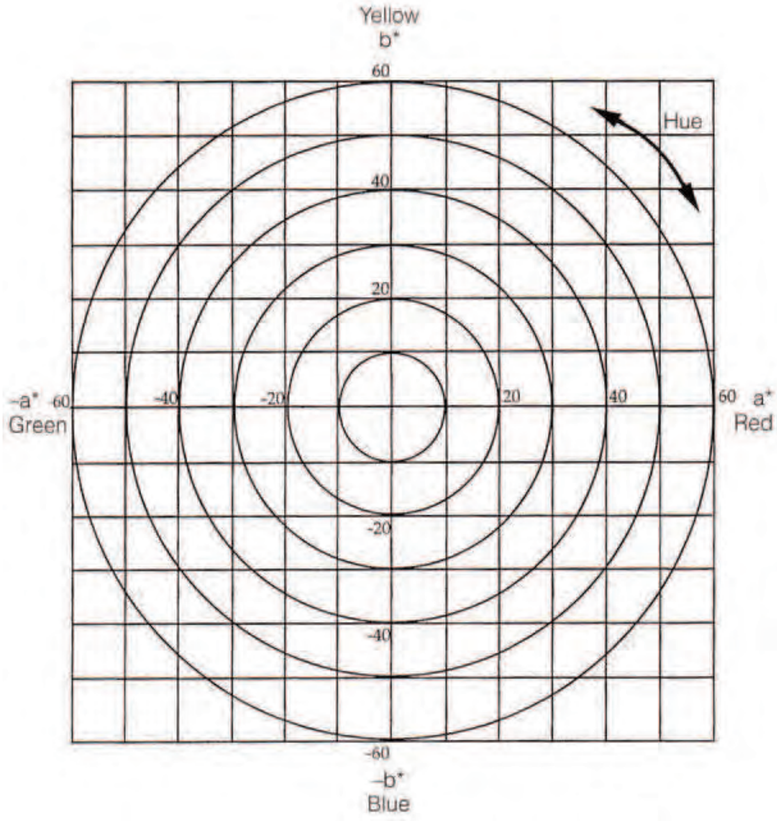


Figure 1
CIELAB color chart.

Research Association ceramic color standards (set CCS-II), the CR-121 consistently yielded results accurate to within one Munsell chip of the nominal value for the entire set of tiles. This performance, comparable to that of many human observers, is acceptable for most field conservation work. The stability of the CR-121, determined by periodic measurement of the CCS-II tiles, showed no pronounced long-term drift over the first two years of measurement. Reproducibility calculations were based on the measurement data from the wall paintings and sculpture (as discussed in the next section).

Measuring Technique

Color measurement of the wall paintings and statues at the Mogao grottoes involved the following procedure: Based on a thorough visual examination, measurement locations were selected to represent all of the colors present at each site. Measurements were made in six caves that were available for other scientific studies. As time permitted, additional measurements were made of both an outdoor painting above Cave 30 and the Pai Fang entryway (Table 1). Locations were recorded photographically and cross-referenced with site maps and floor plans for indexing purposes.

The painted surfaces were prepared for measurement by light dusting with a squirrel-hair brush, under a gentle stream of air produced by a rubber-bulb syringe. This procedure removed any surface dust that may have settled on the paintings that could affect the quality and reproducibility of the data.

Table 1 Measurement totals

Cave no.	Size	Open/closed to public	No. of measurements
35	large	closed	270
29	large	open	279
335	medium	closed	252
323	medium	open	342
232	small	closed	223
236	small	open	225
		Subtotal	1,591
		Outdoor mural above Cave 30	45
		Pai Fang entryway	63
		Total	1,699

Measurement totals by dynasty: Tang:	1,168
Song:	261
Qing:	270

Because of the inhomogeneity and irregularity of the painted surfaces and the difficulty in precisely locating the measuring head at each desired point, single measurements at each location could yield misleading results. Accordingly, three locations were selected within each colored area, each of which was measured three times. Measurement reproducibility was calculated from the three measurements at each area.

Results and Discussion

Color measurement data were entered into a database for archival purposes and for subsequent statistical and graphical interpretation. Tabulated data were sorted by cave, dynasty, and color. Because little or no information can be obtained from the measurement data of neutrals (black or white), these measurement data were not evaluated.

As mentioned, replicate measurements of each colored area were made in order to establish the limits of perceptible color change that can be measured by the CR-121. Standard deviations were calculated for the triplicate measurements for each of the three chromaticity variables and averaged over the entire set of 1,699 measurements. The one-sigma results are ± 0.3 Y, ± 0.001 x,y.

CIELAB charts of the data acquired at each site illustrate the range of palette found in the paintings and statues and are useful for comparing colors from different locations. Figures 2–4 show marked similarity of the palettes between pairs of matched caves (note, for example, the consistent overlay of the data for the small caves). The numbers illustrate that the pairs of caves share similar color schemes (besides the similarities in physical dimensions and dynastic period).

Figure 2
CIELAB data from small caves in the Mogao grottoes. Cave 236 is open to the public; Cave 232 is closed to the public.

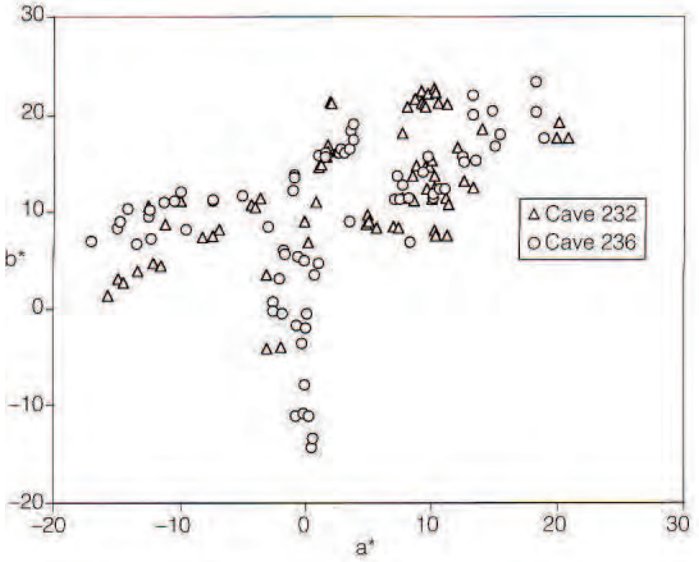


Figure 3
CIELAB data from medium caves in the Mogao grottoes. Cave 323 is open to the public; Cave 335 is closed to the public.

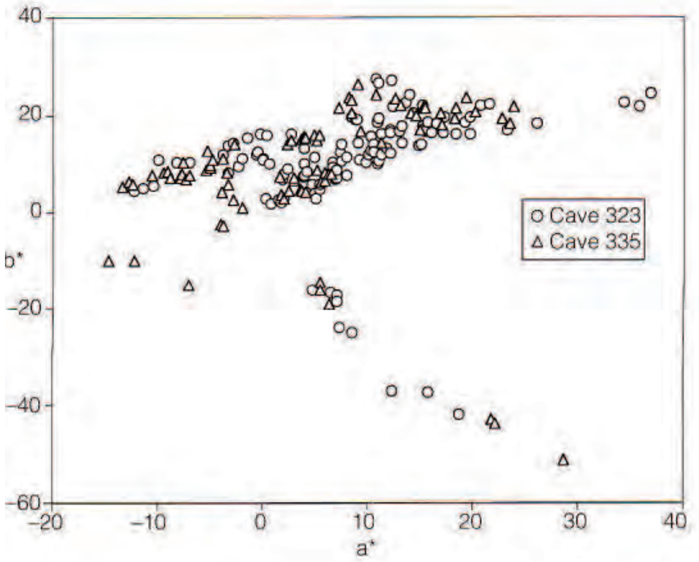


Figure 4
CIELAB data from large caves in the Mogao grottoes. Cave 29 is open to the public; Cave 35 is closed to the public.

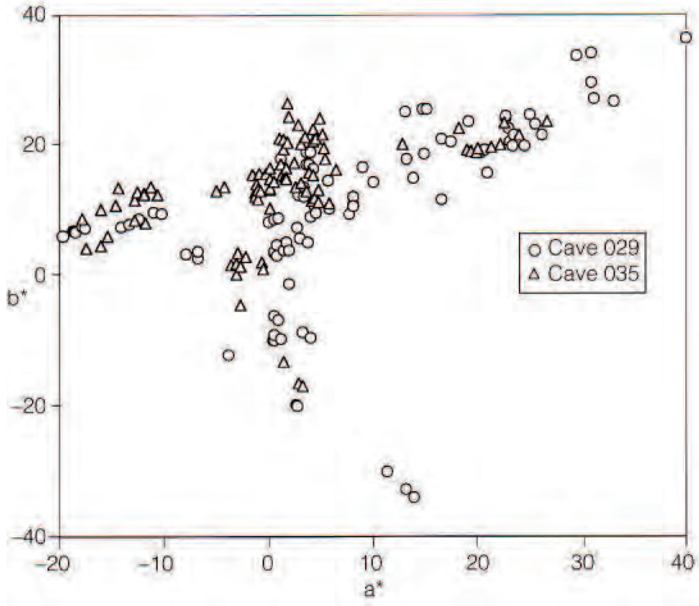
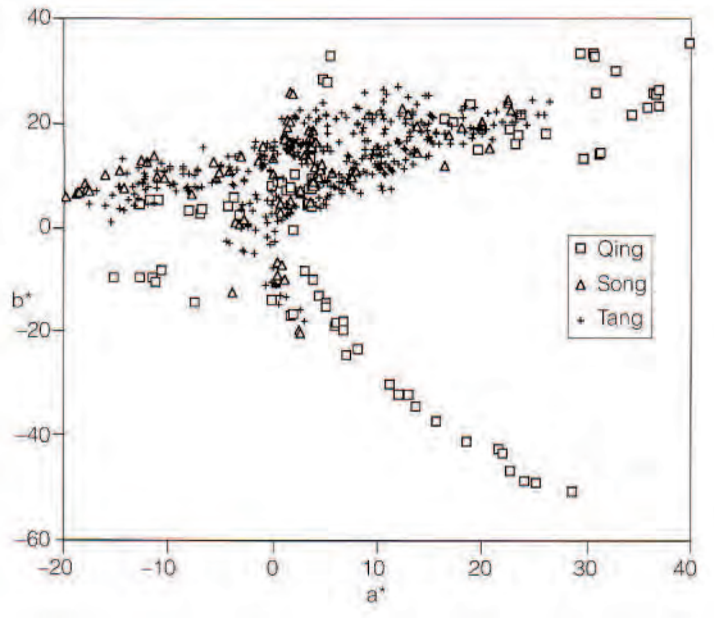


Figure 5
CIELAB data from the Mogao grottoes, sorted by dynasty.



The colors used in the Tang- and Song-dynasty paintings exhibit very low saturation, as evidenced by the closeness of the measurement data to the coordinates of the white-light source in Figure 5. On the other hand, Qing-dynasty paintings have significantly higher levels of saturation, presumably because the painted surfaces are cleaner and less weathered than earlier paintings. Because of this, Qing paintings can be readily distinguished from paintings made in other dynastic periods solely on the basis of color data. Although little distinction can be made between Tang and Song paintings, a complete statistical analysis of a large number of Tang and Song paintings may reveal certain trends that would permit differentiation between paintings from these two dynasties.

Conclusions

The utility of the color monitoring data lies in the establishment of a permanent record of the colors of the cave paintings and statues at the Mogao grottoes as they presently appear. From these data, a master color record for each cave and statue can be compiled. Ultimately, the color record will be a benchmark against which the success of any future preservation efforts will be judged.

Acknowledgments

The authors wish to thank Neville Agnew, associate director, programs, the Getty Conservation Institute, for direction during this project. Max Saltzman, expert on color technology, provided invaluable information and insight on all aspects of this work.

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Scientific Examination of the Sculptural Polychromy of Cave 6 at Yungang

Francesca Piqué

The principal objective of the research described here[1] was to determine the nature and condition of the original and added materials of the paint layers and renders in Cave 6 at the Yungang grottoes. This study forms part of an overall program of investigation of the site by the Getty Conservation Institute and the State Bureau of Cultural Relics, who are collaborating on long-term conservation projects at Yungang and Dunhuang (Agnew and Huang herein).

The Yungang grottoes are Buddhist cave temples located in northern China, in Shanxi Province, near the Great Wall and the Mongolian border, though not specifically on the Silk Road.[2] Construction began at Yungang in 460 C.E., following the establishment of the capital of the Northern Wei emperor at Pingchang (modern Datong), about 15 km to the east. The caves were excavated in the south face of a sandstone cliff 800 m in length and 30–60 m in height (Fig. 1). There are fifty-three major caves, numbered from east to west, as well as fifty-one thousand niches and eleven hundred other smaller caves also excavated in the cliff stretch. The ruins of a fort, built in the Ming dynasty, are still present on top of the cliff. The work at Yungang lasted until the capital was moved south to Luoyang in 494 (Knauer 1983:29–33; Destenay 1986:877). One of the

Figure 1
Yungang grottoes, general view of the western part of the south face of the cliff.

causes of the extreme deterioration of the cliff face is the erosion produced by the rainwater that runs down the inclined edge of the cliff top and washes off any loose material or particles of stone.

The concept of excavating cave temples from cliffs originated in India and spread from there to Afghanistan, Central Asia, and China. The first major Chinese Buddhist temple was built in the fourth century at Dunhuang (Falco Howard 1983:8). After the Northern Wei conquered the Gansu region in 439 C.E., thirty thousand families and three thousand monks were moved from Liangzhou-Wuwei, near Dunhuang, to the dynasty's new capital at Pingchang. This is of great importance because both the Buddhist doctrine and (most interesting for this research) the technique of excavating cave temples moved with these people from the west to the east. It is very likely that some of the same people who worked at Dunhuang were also involved in the early construction at Yungang. Indeed, the monk Tan-yao, who began and directed the excavation and carving work, came from Liangzhou-Wuwei in Gansu Province (Knauer 1983:33; Destenay 1986:877; Juliano 1984:81; Sickman and Soper 1956:90).

Cave 6 was built between 465 and 494 C.E. by Emperor Xiao Wen in memory of his mother and is one of the richest of the sites (Yungang Institute 1977:8; Destenay 1986:885). The cave is square in plan, with an almost square tower, or stupa pillar, at its center that rises to the ceiling. The entire interior surface of the cave is carved and painted; given the three-dimensional surface of the sculpture, the estimated surface area is approximately 1,000 m^2. Within this large area vast differences exist, in terms of condition, number of apparent repainting schemes, and materials used (Fig. 2). The upper and lower stories of the perimeter walls are each divided into three niches. Those of the upper stories house standing

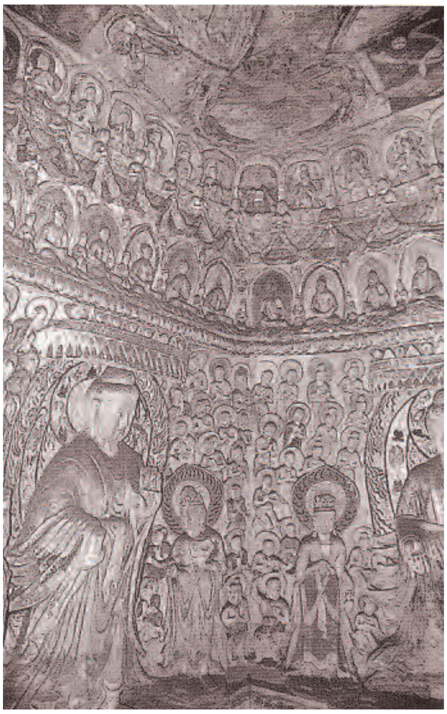

Figure 2
Cave 6 interior, view of the southeastern corner of the upper story, showing painted walls, niches, and Buddhist sculptures. Here the carving is particularly well preserved. Thick deposits of dust are noticeable, particularly on the shoulder of the standing Buddha and the cornice that separates the lower from the upper story.

Buddhas surrounded by bodhisattvas, monks, and celestial flying figures. During sample collection, it was evident that there were at least three repainting phases, that the polychromy was brittle, and that it tended to fracture between paint layers and to separate from the support. Later analysis showed that there were many repainting phases (up to twelve), each composed of at least two layers. For these reasons, the identification of the original painting scheme and subsequent repainting phases was a difficult task. It was done by correlating the historical information and observation on-site with the stratigraphic evidence from the samples and the analytical results.

The history of the condition of Cave 6 is largely reflective of the various events that occurred at Yungang over the centuries, summarized in Table 1.[3] While much more information is available for recent events than for earlier ones, it is possible to relate restoration of the site with the destruction and rebuilding episodes usually associated with power struggles and dynastic wars. However, dates for restoration and repainting in a specific cave are seldom recorded, and therefore the association of a historical event with a particular repainting phase in Cave 6 has been made here only as a hypothesis.

The original materials of the polychrome sculpture were studied with optical and electron microscopy, microchemical tests, infrared microspectroscopy, X-ray diffraction (XRD), and energy-dispersive X-ray microanalysis (EDX). Pro forma examination and sampling were used to follow a coherent method of examination on-site and to collect all information on the samples. Each sample and sample location was also graphically and photographically documented.

Original Scheme

The primary purpose of the research was to determine the nature of the original scheme of polychromy, which was found to be characterized by a single, clay-based preparation layer and a single paint layer (Fig. 3). The preparation layer provides a smooth, compact surface as well as a background color for the paint layer. EDX analysis of the preparation showed the presence of large amounts of silica and aluminum and a small amount of potassium. The white material, visible as a large lump just under the paint layer, was identified by XRD as anglesite ($PbSO_4$) (JCPDS file 5-0577).

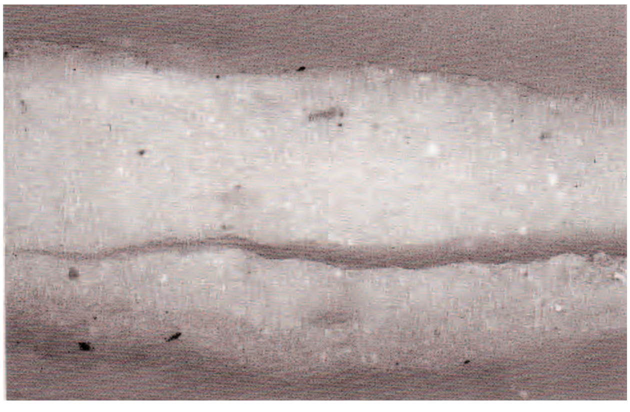

Figure 3
Example of cross section of original scheme. Cross section (×450) of a sample taken from the stupa pillar, south face, lower story, left arm of the fourth figure from the east. Starting from the upper part, the cross section shows a yellow-earth paint layer over a white, single-layer, clay-based preparation (original scheme).

Six pigments were identified in the original scheme. The resulting palette included a deep blue (natural ultramarine), a pale yellow (yellow earth), and several reds (vermilion, red lead, and red earth). It is surprising, particularly in comparison with a comprehensive compilation on contemporary paintings in Central Asia (Piqué 1992), that there is apparently no green pigment used in the original scheme. It is possible that green does occur but was not sampled during the present study, and this should be borne in mind in any future studies of this cave.

The yellow is an earth applied thinly over a white preparation (Fig. 3). The red pigments predominate in variety and use. Vermilion, red lead, and red earth were identified; all are common pigments used in Chinese polychromy. Vermilion and red lead were always applied over a red preparation. Red lead was found in all cases to have converted to plattnerite (PbO_2) (Fig. 4).[4] Plattnerite is the oxidation product of lead-containing pigments and occurs frequently in both Asian and Western paintings. Although the conversion process of lead white—$2PbCO_3 \cdot Pb(OH)_2$—has been well studied, that involving red lead (Pb_3O_4) has not been considered in detail. The oxidation of white lead to plattnerite (Pb^{2+} to Pb^{4+}) occurs by the following equation:

$$2PbCO_3 \cdot Pb(OH)_2 + 6OH^- = 3PbO_2 + 2CO_2 + 4H_2O + 6e^-$$

It is generally assumed that red lead conversion to plattnerite occurs by a similar oxidation process. However, experiments carried out at Dunhuang indicate that an intermediate step occurs, involving the formation of lead white (Li 1990:64–66). This seems to indicate that the conversion process is more complex (involving an initial alteration to lead carbonate) than has been previously considered for the conversion of lead white, formerly presumed to be analogous.[5]

Lead sulfate was identified by XRD in some of the white preparation layers of the original painting scheme (Fig. 3). In white preparation layers not from the original scheme, the high content of lead and sulfur shown by EDX analysis and examination by optical microscopy again suggested the possible presence of lead sulfate. It is notable that in two of

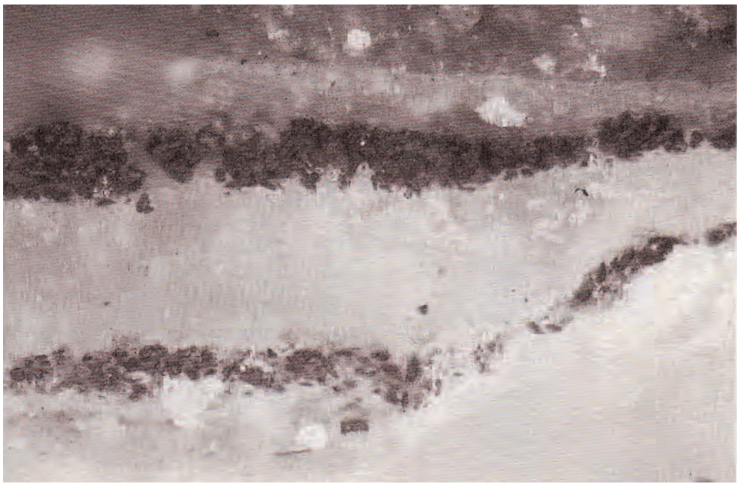

Figure 4
Cross section (×570) of original, first, and later schemes from a sample taken from the stupa pillar, east face, upper story, from the tunic of the central standing Buddha. Starting from the lower part, the cross section shows the white support, the red clay-based preparation layer, and red lead (completely converted to plattnerite) from the original painting scheme. From the first repainting scheme, a white single-layer preparation, composed of clay and gypsum, and darkened red lead are visible. From the repainting phase, a white clay-based preparation layer and a red paint layer, composed of red earth mixed with clay and gypsum, are visible.

these samples the lead-containing mixture had partially darkened. The dark material is very likely to be plattnerite because of the optical and elemental similarities with plattnerite as identified by XRD. Analysis by EDX of both darkened and unaltered particles shows a high content of lead and sulfur, but the lead:sulfur ratio is greater in the darkened particles, consistent with the formation of PbO_2 to the detriment of $PbSO_4$.

In the original scheme, the blue is a dark, natural ultramarine of high quality and large particle size, thickly applied. The sample shown in Figure 5 was collected in an area where much of the sculptural polychromy has deteriorated and the paint layer is almost completely lost in places. In this zone, traces of green thought to be part of the original scheme were identified and sampled. Subsequent examination of the cross section revealed the presence of this original paint layer composed of natural ultramarine below the green. The use of natural ultramarine at this early date is interesting; the mineral has been ascribed to various sources in Persia, China, and Tibet. The best quality lapis lazuli comes from Badakhshan in northeastern Afghanistan. Gettens identified ultramarine in fifth-century wall paintings from Kizil in Chinese Turkestan (Gettens 1938b:287–88). However, Kizil is located only 700 km from Badakhshan, and lapis lazuli would therefore have been much more easily available there than at Yungang, several thousand kilometers away.

First Repainting Scheme

A possible date for the first repainting scheme is 640 C.E.; at that time, during the early Tang dynasty, Yungang was incorporated in the prefecture of Yuncheng, and work was resumed at the Buddhist site (Table 1). Contemporary historical records report that the monk Yen was charged specifically with repairing the Northern Wei sculptures. Although this evidence is not conclusive, this is the first likely occasion for the repainting of Cave 6, some 150 years after its construction.

The first repainting scheme was found to be composed of only two colors: green, mainly composed of atacamite with some malachite and green earth; and red, from red lead converted to plattnerite (as in the original scheme). It seems odd that the palette would be so restricted; although this may be a function of the sampling, it may suggest that the

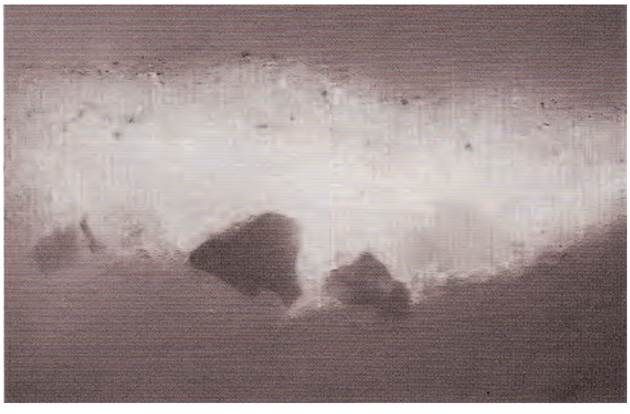

Figure 5
In this cross section (×490), starting from the lower part, the following stratigraphy can be seen: natural ultramarine (original scheme); clay and lead white and/or sulfate preparation, covered by a clay-based preparation (first repainting scheme—the green paint layer is not clearly visible).

first repainting scheme was carried out selectively within the cave.

Atacamite, one of three isomorphs (with paratacamite and botallackite) with the formula $Cu_2Cl(OH)_3$, occasionally mixed with some malachite and possibly green earth, was identified by XRD in six of the eight samples of the first repainting scheme. The optical characteristics of atacamite found in Cave 6—transparent green, globular rosettes with undular extinction, the occasional presence of a central dark core, and high relief (Fig. 6)—differ considerably from those of the natural mineral and may indicate a synthetic origin (Naumova, Pisareva, and Nechiporenko 1990:84). This type of mineral green pigment is commonly found at Dunhuang in wall paintings of almost all dynasties, including the Northern Wei (Xu et al. 1989; Moffatt et al. 1988:9).

Later Repainting Phases

As mentioned earlier, the substantial historical evidence indicating refurbishment, redecoration, and repainting at Yungang cannot be directly correlated with the scientific evidence of the stratigraphy. There are, however, several significant events that may have occasioned repainting in Cave 6, indicated in the chronology provided in Table 1. The general problems encountered in determining early painting schemes—including discontinuity due to partial repainting and/or partial loss—are compounded when trying to accurately identify successive repainting schemes. It was decided, therefore, to generally and collectively characterize stratigraphies not attributable to either the original or the first repainting scheme.

The technique of the various repainting phases that took place later does not differ significantly from that of the two earliest schemes. Dependence on the use of a ground and the tendency to apply paint in a single layer persist. The palette of the later phases—consisting of red, green, blue, yellow, black, and gold—is more extensive than that of the original and first repainting schemes. Three types of blue pigment are present: azurite, synthetic ultramarine, and an early type of Prussian blue. The range of yellows was expanded to include orpiment and massicot. Carbon black is also commonly found. An interesting addition is that of gold leaf, which was probably used to imitate gilded bronze sculpture. It was used on flesh areas, and remnants of gilding can be found on all of the figures. In one sample in which gold is used for flesh tone, there are four gold

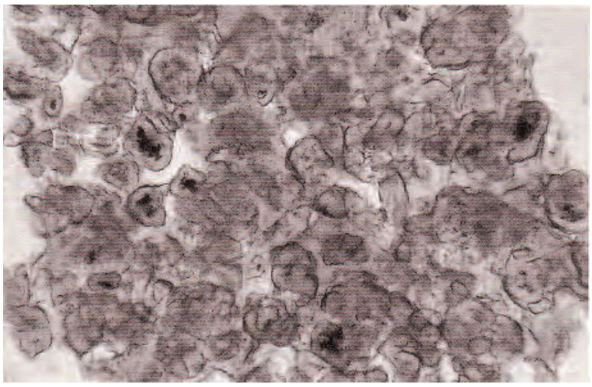

Figure 6
Photomicrograph (×450) in transmitted light of the green pigment found to be mainly composed of atacamite (by XRD, JCPDS file 25–269).

Table 1 Chronology, indicating possible repainting schemes

Date	Cave 6	Site	Historical events	Source
221 B.C.E.			First unification of China under Ch'in-shihuang-ti, who burned Confucian books	Knauer 1983:28
207 B.C.E.–220 C.E.		The site was important for its strategic position and was called Pingchang	Han Dynasty: resurgent Confucianism, funerary art	Knauer 1983:28
111 B.C.E.			Dunhuang established as a prefecture	Dunhuang Institute of Cultural Relics 1983:251
First century C.E.			Buddhism reached China along Silk Road from India	Knauer 1983:28
Early fourth century C.E.			Toba tartars (future Northern Wei dynasty) occupied territories north of Yellow River	Knauer 1983:28
386–535			Northern Wei dynasty: Buddhism became imperial religion	Falco Howard 1983:7
398		Northern Wei capital established at Pingchang (Datong)	Reign of emperor Toba Kuei	Knauer 1983:29 Destenay 1986:877
439		3,000 captive monks and 30,000 families moved from Liangzhou-Wuwei in Gansu Province (near Dunhuang) to Datong	Emperor Tai Wu conquers Gansu Province (including Dunhuang)	Knauer 1983:33 Destenay 1986:877 Juliano 1984:81 Sickman and Soper 1956:90
446–452			Buddhism persecution: disruption of temples and monastery	Knauer 1983:29 Sickman and Soper 1956:87
452–454			Restoration of Buddhism	Knauer 1983:30 Sickman and Soper 1956:87
455		Five Indian monks, sculptors, and painters arrived in Datong		Destenay 1986:878
460–485		Beginning of work at Yungang, directed by the monk Tan-yao (who was from Liangzhou)		Destenay 1986:878 Sickman and Soper 1956:87 Juliano 1984:82
465–494	Construction by Emperor Xiao Wen (471–500) in memory of his mother			Yungang Institute 1977:8 Destenay 1986:885
494	Completed when the capital was moved to Luoyang	End of most active work but some continues; site remains an important Buddhist center	Capital moved from Datong to Luoyang (south)	Yungang Institute 1977:10 Sickman and Soper 1956:87 Knauer 1983:32–33
523		Rebels controlled Pingchang for 7 years; beginning of decline of Yungang as Buddhist center		Yungang Institute 1977:13
640	*Possible repainting phase*	Construction work resumed: a monk, Yen, in charge of repairing the Northern Wei images	Yungang incorporated into the prefecture of Yuncheng (early Tang dynasty, 618–906)	Yungang Institute 1977:13

Table 1 continued

Date	Cave 6	Site	Historical events	Source
1049–1059	Site of the Tienkung Monastery *Possible repainting phase and first use of mud plaster repair*	Construction of 10 wooden monasteries and other structures in front of the caves. Repair of 1,876 large and small Buddhist images; some images added	1044: Datong established as one of the five capitals; revival of Buddhism	Yungang Institute 1977:13 Knauer 1983:33 Mizuno and Nagahiro 1955: vol. 2, 56–57 Juliano 1984:85
1122		Attack by Jin army; all 10 monasteries were burnt	Liao-Jin dynasties war episodes	Yungang Institute 1977:8 Juliano 1984:85
1143–1146	*Possible repainting phase*	Cave temples repaired by monk Ping Huei	Jin dynasty (1125–1234)	Yungang Institute 1977:14
1305		Strong earthquake destroyed 4,800 houses; 1,400 people killed	Yuan dynasty (1271–1368)	Xie 1992
1548–1558	*Possible repainting phase*	Caves were repaired and restored	Ming dynasty (1368–1644)	Yungang Institute 1977:14
1644		All buildings destroyed. Any wooden structure visible now is post-1644	Qing dynasty (1644–1911), occupation of Datong	Yungang Institute 1977:14 Juliano 1984:85
1651	Wooden monastery built in front of Caves 5 and 6 *Possible repainting scheme*	Under emperor Shun Zhi, work carried out		Yungang Institute 1977:14 Knauer 1983:33 Tablet in Cave 5 Juliano 1984:50
1696–1698	*Possible repainting scheme*	Emperor Kang Xi visited the site. The monastery was reconstructed		Tablet in Cave 5 Yungang Institute 1977:14 Destenay 1986:883
1769	*Possible repainting scheme*	The monasteries repaired: gilding of flesh areas on figures	Reign of emperor Qian Long (1736–1796)	Yungang Institute 1977:14
1861		Construction of buildings in front of the caves		Tablet in Cave 5
1876		Small house built in front of caves: decoration of Buddhas		Tablet in Cave 6
1892	*Possible repainting scheme*	Visit of emperor: general cleaning and repainting of the caves, Caves 9–13 gilded and decorated	Reign of emperor Guang Xu (1875–1909)	Tablets in Cave 9 (set up in 1920)
1938–1945	Heavy repainting on stupa and soffit recorded	Mizuno and Nagahiro worked at Yungang		Knauer 1983:27 Mizuno and Nagahiro 1955
1940		Precinct built around the site		Mizuno and Nagahiro 1955: vol. 2, 56
1949		Flood; after liberation, works were carried out at the site		Knauer 1983:33 Huang 1992 Tablet in Cave 7
1955	Wooden temple in front of Caves 5, 6, and 7 restored	Foundation of the Institute for the Preservation of the Yungang Caves. Entire site cleared		Destenay 1986:885
1988		Beginning of GCI project		
1992		Archaeological excavation in front of cave 20: gilded fragments found		

layers but no evidence of any other type of colored paint layer, indicating that gold was used during the last four surviving repainting phases.

Comparison with Previous Scientific Examination of Chinese Polychromy

Technical literature provides substantial data for comparison with the results from Cave 6 at Yungang. Relevant technical literature, selected on the basis of date, site, and type of object, is summarized in Table 2. Articles are arranged by the date of publication, and the analytical methods used for examination are given. It is evident from this table that there is a time gap between the early work of Gettens, carried out with polarized-light microscopy (PLM), microchemical tests (MCT), and recent instrumental analysis beginning in the 1980s. Moreover, there is no scientific examination on sculptural polychromy of the fifth century, which would be directly comparable to that of Yungang. Substantial data remains,

Table 2 Summary of relevant technical literature on Chinese and Central Asian polychromy

Date of publication	Author	Analytical methods	Object date	Object type	Site or culture[1]
1921	Church	PLM, MCT	not given	wall paintings	Dunhuang and others
1935[2]	Gettens	PLM, MCT	C15	wall paintings	Dunhuang
1936[2]	Gettens	PLM, MCT	Tang dynasty (618–907) and earlier	wall paintings and sculptures	Dunhuang
1938c	Gettens	PLM, MCT	Ming dynasty (1368–1644)	wall paintings	Hua Yen Ssu Shanxi
1938a	Gettens	PLM, MCT	late C6	wall paintings	Bamian, Afghanistan
1938b	Gettens	PLM, MCT	C5–9	wall paintings	Kizil, Chinese Turkestan
1982, 1983	Moffatt and Adair	XRD, FTIR, SEM-EDX	1279–1368 Yuan dynasty	wall paintings	Shanxi, near Yung-Lo
1992	West FitzHugh and Zycherman	PLM, XRD, SEM-EDX	204 B.C.E.–221 C.E. Han dynasty	blue pigment	Chinese
1985	Larson and Kerr	PLM, MCT, XRF, GC-MS	1115–1234 Jin dynasty	sculpture	Putuo Shan Zhejian, East China
1987	Duang et al.	XRD, EPMA	not given	wall paintings	North China
1988	Larson	PLM, MCT, XRF GC-MS	Tang and Jin dynasties and C8–13	sculptures	Chinese
1988	Moffatt et al.	XRD, FT-IR, SEM-EDX	not given	wall paintings	Dunhuang
1989	Dunhuang Academy	XRD	618–907 Tang 960–1271 Song	wall paintings Caves 35 and 232	Dunhuang
1989	Xu et al.	XRD, XRF	from 304–C19 Sixteen to Qing dynasty	wall paintings	Dunhuang
1992	West FitzHugh and Zycherman	PLM, XRD, SEM-EDX	204 B.C.E.–221 C.E. Han dynasty	purple pigment	Chinese

[1]Where the object is unprovenanced, the cultural designation is given instead.

[2]Unpublished reports.

PLM = polarized-light microscopy; MCT = microchemical test; XRD = X-ray diffraction; FT-IR = Fourier-transform infrared spectroscopy; SEM-EDX = scanning electron microscopy-energy dispersive X-ray spectrometry; XRF = X-ray fluorescence; GC-MS = gas chromatography-mass spectrometry.

nevertheless, and this has been extracted and organized by pigment in Piqué 1992, tables 6.2–6.17. Most past analytical work has been undertaken on wall paintings, particularly at Dunhuang; but data on sculptural polychromy is also available and of great interest. The most striking conclusion obtained from this tabulation is that the techniques of the polychromy do not vary significantly in relation to the type of support—whether stone, mud, or wood. In fact, the support does not correlate significantly with the object type; both wall paintings and sculptures may be on either mud or stone. The common basic technique, consistent with the findings at Yungang, is the use of a clay-based ground under the paint layers.

Areas for Future Study

This study of the polychromy of Cave 6 at Yungang has provided significant information on the original and subsequent painting schemes of the sculptured decoration. However, due to the constraints on in situ examination, sampling, and analysis, a number of issues were not fully resolved and require further research. Moreover, consideration of the historical and technological importance of the painted decoration of Cave 6 within the wider context of Central Asian and Chinese polychromy was severely restricted by the relative paucity of similar research and by the lack of access to much of the primary Chinese literature on paintings. The principal issues requiring further research are the alteration of lead-containing pigments, the synthesis and use of atacamite, the nature and use of clays, the nature and use of organic binders, and the absence of green in the palette of the original scheme.

A conspicuous finding was the deterioration of lead. All the samples of red lead from the original scheme were found to be entirely altered to plattnerite, whereas in the later layers, red lead is found unaltered, partially altered, and fully altered. Additionally, both lead white and lead sulfate were found to be partially converted to plattnerite. Clearly, the mechanism of and conditions for the conversion of these lead-containing pigments to lead dioxide is of considerable interest, particularly with regard to implications they may hold for conservation.

Another area that may prove fruitful for further investigation is the synthesis and use of atacamite. The present study has not only demonstrated its extensive use in Cave 6 over a long period of time but also suggests that other tentatively or inconclusively identified greens in Chinese polychromy may be atacamite. Copper-chloride greens are increasingly being identified in Western medieval paintings, though in many cases they may be the alteration products of copper-carbonate greens. Their apparently widespread use in Chinese paintings during the same period is significant, and further study would be of interest not only in the context of Chinese painting technology but also in regard to Western practice.

Some of the green particles that were found mixed with atacamite and malachite were tentatively identified as green earth, even though the elemental analysis of the green mixture showed that the main components were copper and chloride. Other green particles, however, did not show any characteristic features in transmitted-light examination. A recent study

Figure 7
Cave 6, stupa pillar, east face, lower story, lower part of third figure from west, enlarged detail showing traces of paint layer flaking from the stone support. Large amounts of dust are deposited at the feet of the figure and also behind the flakes of the paint.

(Martin and Eveno 1992:785) has shown that copper pigments often have heterogeneous composition, and that to fully understand the nature of such a mixture, both XRD and elemental analysis should be carried out on all types of particles present.

The use of clay seems to be the most characteristic feature of Central Asian and Chinese polychromy. The tentative hypothesis that fired clay was ground and used for at least some of the preparation layers of Cave 6 certainly merits further investigation. It would, therefore, be highly desirable to undertake an exhaustive study of clays: their components and their physical and aesthetic functions. This would require in-depth analysis of clay types, their mineral inclusions, and the probable organic binders used, as well as their correlation with paint layers to interpret their function within the overall stratigraphy.

It has not been possible during this research to undertake analysis of the organic binding media used. Clearly, this would be highly desirable, particularly with regard to the implications for future conservation. However, present insights into the various painting phases revealed by the components and layer structure of the polychromy are a necessary preliminary step for any such study.

While the general conclusions regarding the relationship of the polychromy of Cave 6 to the wider context of Central Asian and Chinese paintings seem to be valid, the constraints on making such conclusions are considerable, as there is little comparable technical analysis. The important work now being carried out by the Dunhuang Academy is doing much to elucidate the technologies of the paintings of various periods in Dunhuang. However, Yungang is almost 2,000 km east of Dunhuang, thus separated from direct influences carried along the Silk Road; the extent to which the technology of its polychromy reflects or adapts early Chinese (as opposed to Central Asian) techniques is simply not known. Apart from the technical examination of earlier Chinese polychromy (particularly of the Han and Sixteen dynasties), another obvious source of the context of the Yungang paintings would be primary sources and documents. These are considerable, and to evaluate them would clearly require expert knowledge of both their language and history.

As indicated, some of the further research proposed here would have implications for the conservation of polychromy, particularly analysis of the media and investigation of the causes of lead alteration. However, an additional factor is the serious threat posed by the development of the coal industry at adjacent Datong, one of China's largest coal producers, whereby a fine black dust is continuously and heavily deposited on the sculptures (Figs. 2, 7). Apart from the physical and chemical interaction this may cause (Christoforou, Salmon, and Cass herein), an immediate and serious danger is the dusting regularly undertaken to remove this deposit. Considering the extremely fragile condition of the surviving polychromy—often tenuous adhesion between various layers of paint, and the widespread flaking evident (Fig. 7)—dusting is likely to be one of the major factors presently causing the loss of the paint layers. It is therefore necessary, first, to attempt to reduce the amount of dust deposited and,

second, to improve the methods of dusting. Obviously, the problem of flaking that is common to the entire site should also be resolved; however, this would require an extensive investigation both of the causes and of suitable conservation methods and materials.

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Notes

1 This research project was undertaken by the author in partial fulfillment of her M.S. degree in wall painting conservation at the Courtauld Institute of Art. The analytical work was carried out at the Getty Conservation Institute.

2 See map of Asia, pages xiv–xv.

3 Bibliographic citations for the information included in the chronology are given in Table 1 and are not repeated here.

4 Plattnerite (PbO_2) may occur as the oxidation product of either white or red lead (Giovannoni et al. 1990:21), but the original pigment cannot be determined analytically from the altered material. Consequently, determination of the original color is made on the basis of circumstantial evidence—particularly the presence of unconverted particles in the paint layer and the likely coloristic intent—as indicators of the original pigment. In this case, the strongest evidence indicating this is the use of a red preparation beneath all samples.

5 Considering that in the red lead (Pb_3O_4) the lead is not at a single state of oxidation but rather two lead atoms are found at the lower oxidation state (Pb^{2+}) and one at the higher oxidation state (Pb^{4+}), and lead white contains only Pb^{2+}, this type of process would be composed of a first reduction (of the one Pb^{4+} atom in red lead to Pb^{2+} in white lead) followed by an oxidation of Pb^{2+} to Pb^{4+} (oxidation state in plattnerite).

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Pigment Analysis of Polychrome Statuary and Wall Paintings of the Tiantishan Grottoes

Zhou Guoxin, Zhang Jianquan, and Cheng Huaiwan

The Tiantishan Grottoes are situated on the Huangyang River, about 60 km south of Wuwei (originally Liangzhou) and were excavated during the Northern Liang dynasty (397–439 C.E.). Carving and decoration of the grottoes continued throughout the Northern Wei, Tang, and Ming dynasties, leaving many precious cultural relics inside these grottos.

On the basis of the style, content, and inscriptions on the wall paintings and landforms, archaeologists believe that the Tiantishan grottoes may be the Liangzhou grottoes mentioned in historical documents, such as the *Fa Yuan Zhu Lin*. According to historical records, the Liangzhou grottoes were ranked with the Yungang and Longmen grottoes as the three major cave temple sites to have exerted profound influence on the development of Chinese painting and sculpture. If the Tiantishan and Liangzhou grottoes are actually one and the same, research and protection of this site becomes even more meaningful and important.

Because of the construction of the Huangyang River reservoir in 1960, the Gansu People's Government approved moving the wall paintings and polychrome statues of the grottoes, with the exception of seven cliff statues, to the Gansu Provincial Museum for preservation. In conjunction with the restoration and conservation of the Tiantishan relics, the authors collected and analyzed ninety-six samples from the Northern Liang, Northern Wei, Tang, and Ming dynasties and performed comprehensive analyses of their pigments.

Experimental Principles and Methods

X-ray diffraction analysis is capable of accurate and rapid analyses of pigments from polychrome statues and wall paintings. Only small quantities of sample are required, it is not necessary to chemically separate the samples, and the samples are not destroyed. The samples that have been analyzed can be stored in the form of index cards for future comparative use. X-ray fluorescence analysis is an important auxiliary technique to X-ray diffraction that can increase the reliability of the results of analysis (Xu, Zhou, and Li 1983).

Analytical Results

Detailed records were made of the sampling sites at the time of sampling. Results of the analyses are presented in Table 1. The pigments that were used over the course of the successive dynasties in the Tiantishan grottoes and the circumstances of their use can be ascertained from the table.

In the samples taken from the Northern Liang dynasty, gypsum and anhydrite were the major white pigments, cinnabar was the red pigment, and malachite was the green pigment. Lead hydroxychloride and lead sulfate were used in addition to gypsum and anhydrite for color blending.

In the Northern Wei samples, anhydrite and kaolin were the major white pigments; cinnabar and malachite were used; and azurite was the blue pigment with gypsum, anhydrite, and kaolin added for color blending.

In the Tang dynasty samples, the Tang polychrome sculpture had two layers. Gypsum and lead white were the major white pigments, cinnabar and minium were the red pigments, and azurite and malachite were also used. Gold powder and gold leaf were used for the gold color, and gypsum and lead white were used during the color blending process. For the outer layer, the major white pigments were lead white, lead sulfate, gypsum, and kaolin; the red pigments were cinnabar and minium; the blue pigment was azurite; the green pigments were malachite, basic copper chloride, and hydrated basic copper chloride; the brown pigments were lead dioxide (an oxidation product of minium); and the gold pigments were gold powder and gold foil. In addition to lead white, gypsum, lead sulfate, and kaolin, many other pigments, such as lead hydroxychloride, chalk, and a natural mineral—leadhillite, $PbSO_4 \cdot 2PbCO_3 \cdot Pb(OH)_2$—were added for color blending. The colors used were complex. The white pigment for the Tang wall paintings was gypsum, and the red pigment was hematite.

In the Ming dynasty wall paintings sampled, kaolin, gypsum, and lead sulfate were the major white pigments. The red pigments were cinnabar and minium; the green pigments were malachite, basic copper chloride, and hydrated basic copper chloride; the blue pigment was azurite; and the yellow pigment was orpiment. Soot was the black pigment used during all of the dynasties mentioned here.

Discussion

Calcium oxalates (calcium oxalate monohydrate and calcium oxalate dihydrate), which are compounds of organic origin, are commonly associated with plant fossils. Many samples examined in this study contained calcium oxalates. Similar results were also observed in the Maijishan grottoes of Gansu Province and the Yungang grottoes of Shanxi Province (Zhou 1991; X-ray Diffractometer Users' Association 1983). There are no specific reports as to whether calcium oxalates were used as pigments or whether they were formed later; further study will be required on this matter.

In the present work, the authors found that the colors of the pigments used in the Tiantishan grottoes were rich and vivid. Malachite, atacamite-type basic copper chloride, paratacamite basic copper chloride, and hydrated basic copper chloride were used as the green pigments.

Table 1 Pigment analysis results

Dynasty	Cave no.	Sample no.	Color	XRF	XRD	Pigment phases	Note
Northern Liang	4	01	Red		cinnabar, lead chloride, trace calcite, quartz	cinnabar	
Northern Liang	4	02	Black		quartz, mica	ink	
Northern Liang	4	03	Green	Cu, Pb	quartz, lead sulfate, malachite, gypsum	malachite	
Northern Liang	4	04	White		gypsum, trace anhydrite	gypsum, anhydrite	
Northern Wei	1	05	Green		malachite, trace gypsum, kaolin, quartz	malachite	
Northern Wei	1	06	Red		cinnabar, quartz, trace gypsum, kaolin	cinnabar	
Northern Wei	1	07	Blue-green		azurite, quartz, feldspar, calcite, anhydrite	azurite	
Northern Wei	1	08	Red		cinnabar, anhydrite, quartz	cinnabar	
Northern Wei	1	09	Black		anhydrite, trace quartz	ink	
Tang	2	10	Ground		quartz, kaolin, calcite, feldspar, mica		inner layer [a]
Tang	2	11	Ground		quartz, kaolin, feldspar, calcite		outer layer
Tang	2	12	White		gypsum, quartz, trace kaolin	gypsum	inner layer
Tang	2	13	Light green		gypsum, malachite, quartz, trace lead white	malachite	inner layer
Tang	2	14	Red		gypsum, minium	minium	inner layer
Tang	2	15	Green		malachite, trace quartz, mica	malachite	outer layer
Tang	2	16	Black		quartz, calcium 2-oxalate, trace gypsum, kaolin	ink	outer layer
Tang	2	17	Red		minium, lead chloride, gypsum, lead hydrochloride	minium	outer layer
Tang	2	18	White		lead sulfate, kaolin, lead white, calcium 2-oxalate	lead sulfate, lead white	outer layer
Tang	2	19	Gold	Pb, Au	lead white, gold powder, trace quartz	gold powder	outer layer
Tang	2	20	Blue		gypsum, calcite, feldspar, quartz, trace gypsum, calcium 2-oxalate	azurite	outer layer
Tang	2	21	Green		malachite, lead white, quartz, trace gypsum	malachite	outer layer
Tang	2	22	White	Pb	gypsum, quartz, lead sulfate, trace calcium oxalate	lead sulfate	outer layer
Tang	2	23	Red		cinnabar, trace kaolin, calcite, minium	cinnabar, minium	outer layer
Tang	2	24	Light yellow	Pb	lead white, quartz	lead white	outer layer
Tang	3	25	Red	Pb, Hg	cinnabar, lead sulfate, minium, kaolin	cinnabar, minium	outer layer
Tang	3	26	White		lead sulfate, lead white, quartz, kaolin	lead sulfate, lead white	outer layer
Tang	3	27	Green		atacamite, quartz, trace kaolin	atacamite	outer layer
Tang	3	28	Blue-black		gypsum, quartz, calcium 2-oxalate, trace kaolin	azurite	outer layer
Tang	3	29	Gold		lead white, gold powder	gold powder	outer layer
Tang	3	30	Blue	Cu, trace Pb	azurite, quartz	azurite	outer layer
Tang	3	31	White		quartz, calcium 2-oxalate, basic lead sulfate	lead sulfate	outer layer
Tang	3	32	White		lead white, quartz, gypsum	lead white, gypsum	inner layer
Tang	3	33	Red		minium, calcium 1-oxalate, cinnabar	minium, cinnabar	outer layer

Table 1 continued

Tang	3	34	Blue-black	Cu, trace Pb	azurite, quartz	azurite	inner layer
Tang	3	35	Blue	Cu, trace Pb	azurite, quartz	azurite	inner layer
Tang	3	36	Green		malachite	malachite	inner layer
Tang	3	37	Red		minium, gypsum	minium	inner layer
Tang	3	38	Red	Pb, Hg	cinnabar, quartz, trace minium, lead white, kaolin	cinnabar, minium	outer layer
Tang	3	39	Brown-black	Pb	minium, quartz, calcite, lead hydrochloride, lead oxide	minium, lead oxide	inner layer
Tang	3	40	Gold		lead white, gold powder, gypsum	gold powder	inner layer
Tang	3	41	Red	Pb, Hg	cinnabar, minium, gypsum	cinnabar, minium	inner layer
Tang	3	42	Green		malachite, gypsum, quartz, lead white	malachite	inner layer
Tang	3	43	Light green	Pb, Au	malachite, lead white, trace quartz	malachite	inner layer
Tang	3	44	White		kaolin, gypsum, trace quartz, lead sulfate, mica	kaolin, gypsum	outer layer
Tang	3	45	Black		quartz, calcium 2-oxalate, basic lead sulfate	ink	outer layer
Tang	3	46	White	Pb	lead white	lead white	same layer
Tang	3	47	Blue		minium, cinnabar, kaolin, quartz		outer layer[b]
Tang	3	48	Red		minium, cinnabar, calcite, trace kaolin	cinnabar, minium	outer layer
Tang	3	49	Dark green		malachite, lead white, quartz	malachite	outer layer
Tang	3	50	Light green		malachite, lead white, quartz, trace calcite, lead sulfate, calcium 2-oxalate	malachite	outer layer
Tang	3	51	Gold	Au, Pb	gold powder, lead white	gold	outer layer
Tang	3	52	Gold	Au, Pb	gold powder, lead white	gold	outer layer
Tang	3	53	Red		cinnabar, minium, quartz, trace calcium 2-oxalate	cinnabar, minium	outer layer
Tang	3	54	Brown	Pb	calcium 2-oxalate, leas sulfate, mica, quartz, minium, lead oxide		outer layer
Tang	3	55	Pink		lead sulfate, quartz, cinnabar, minium, trace mica calcium 2-oxalate	cinnabar, minium	outer layer
Tang	3	56	Red		cinnabar, minium, lead sulfate	cinnabar, minium	outer layer
Tang	3	57	Light green		quartz, lead sulfate, trace malachite, gypsum	malachite	outer layer
Tang	3	58	Blue		azurite, quartz, calcite, feldspar	azurite	outer layer
Tang	3	59	Black		calcite, feldspar, gypsum	ink	outer layer
Tang	3	60	White		lead sulfate, lead white	lead sulfate, lead white	outer layer
Tang	3	61	White		gypsum, anhydrite, lead white	gypsum, anhydrite, lead white	inner layer
Tang	2	62	Black		gypsum, lead white, quartz, feldspar	ink	inner layer
Tang	2	63	Red		cinnabar, gypsum, anhydrite, lead white	cinnabar	inner layer
Tang	2	64	Blue		lead white, azurite, quartz	azurite	inner layer
Tang	2	65	Green		paratacamite, gypsum, quartz, malachite	paratacamite	outer layer
Tang	2	66	Black		quartz, calcium 2-oxalate, lead sulfate, trace gypsum, kaolin, feldspar	ink	outer layer
Tang	3	67	Green		atacamite, calcite, quartz	atacamite	outer layer

Table 1 continued

Tang	3	68	Red		kaolin, gypsum, trace quartz, lead sulfate, mica	cinnabar, minium	outer layer
Tang	3	69	Brown	Pb	quartz, calcium 2-oxalate, basic lead sulfate	minium, lead oxide	inner layer
Tang	3	70	Green	Cu, trace Pb	malachite, gypsum, calcium 2-oxalate	malachite	inner layer
Tang	3	71	White		gypsum, trace cinnabar	gypsum	inner layer [c]
Tang	3	72	Red		gypsum, cinnabar	cinnabar	inner layer
Tang	3	73	Blue	Cu, Ni, trace Pb	azurite, gypsum	azurite	inner layer
Tang	3	74	Black		gypsum	ink	inner layer
Tang	3	75	Green	Cu, trace Pb	gypsum, malachite, quartz	malachite	inner layer
Tang	3	76	White	Pb	lead white, gypsum	lead white, gypsum	inner layer
Tang	8	77	Black	Pb, Fe	gypsum, trace hematite	ink	outer layer
Tang	8	78	Red	Fe	gypsum, quartz, trace hematite, calcium 2-oxalate	hematite	outer layer
Tang	8	79	White	trace Pb, Fe	gypsum	gypsum	outer layer
Ming	2	80	Green		atacamite, hydrated basic copper chloride, calcite	atacamite, paratacamite	
Ming	2	81	White		kaolin, gypsum, anhydrite, calcium 1-oxalate	kaolin, gypsum, anhydrite	
Ming	2	82	Red		cinnabar, minium, lead hydrochloride	cinnabar, minium	
Ming	2	83	Green		atacamite, paratacamite, calcium 2-oxalate	atacamite, paratacamite	
Ming	2	84	Red		cinnabar, quartz, trace kaolin, calcium 2-oxalate	cinnabar	
Ming	2	85	White		gypsum, kaolin, quartz trace calcite, mica, calcium 2-oxalate, lead hydrochloride	gypsum, kaolin	
Ming	2	86	Black		quartz, kaolin, gypsum, mica, calcium 2-oxalate	ink	
Ming	3	87	Blue	Fe	gypsum, calcium 2-oxalate, quartz		see note[d]
Ming	3	88	Red		minium, cinnabar, calcite, kaolin	minium, cinnabar	
Ming	3	89	Green		malachite, quartz, calcite, gypsum, calcium 2-oxalate	malachite	
Ming	3	90	Black		gypsum, kaolin, quartz, calcium 2-oxalate	ink	
Ming	3	91	White		gypsum, calcium 2-oxalate, lead hydrochloride	gypsum, lead hydroxychloride	
Ming	3	92	Blue	Cu, trace Pb	azurite, calcite, quartz	azurite	
Ming	3	93	Green	Cu, trace Pb	atacamite, hydrated basic copper chloride	atacamite, paratacamite	
Ming	3	94	Red	Pb, trace As	minium, kaolin, trace lead white, calcium 2-oxalate	minium	
Ming	3	95	White	Pb	lead sulfate, trace gypsum, kaolin	lead sulfate	
Ming	3	96	Light yellow	As, trace Pb	gypsum, trace kaolin, calcium 2-oxalate, orpiment	gypsum, kaolin, orpiment	

[a]Repainted Tang statues, age of outer layer unknown; all the pigments labeled outer/inner layer belong to this case.

[b]Pigment sample 47 is blue. However, the pigment layer is very thin; part of red pigment sample 48 was incorporated during sampling, and no blue color phase was detected.

[c]Red pigment was mixed in sample 71 during sampling.

[d]No colored phase was detected.

Records of the use of malachite occur in ancient books about painting. Different types of basic copper chlorides probably were the "copper green" pigment recalled by many ancient and modern artists. Copper green is a mineral pigment that is made by artificial methods, and different types may result from different methods of manufacture.

In the Tiantishan grottoes, white pigments containing large quantities of lead were found covering large areas of the paintings. Five types of lead-containing white pigments were identified: lead white, lead sulfate, lead hydroxychloride, lead chloride, and leadhillite. Lead white and lead sulfate were the most commonly used. Gypsum, chalk, anhydrite, and kaolin were also used as white pigments. This extensive use of lead-containing white pigments in grotto wall paintings is rarely seen. It is surmised these pigments were obtained in the region of the Tiantishan grottoes.

There are many different kinds of lead white. The authors have found $PbCO_3 \cdot Pb(OH)_2$; $3PbCO_3 \cdot 2Pb(OH)_2 \cdot H_2O$; $PbCO_3 \cdot Pb(OH)_2 \cdot H_2O$; $2PbCO_3 \cdot Pb(OH)_2$; and $2PbCO_3 \cdot Pb(OH)_2 \cdot H_2O$ in the Mogao grottoes, the Chengde Summer Villa, the Han Tomb in Shou County, Anhui Province, and the wooden pagoda of the Western Xi Tomb in Baoji (Zhou 1990). Lead sulfate was also discovered in one sample from the Mogao grottoes and one sample from the Maijishan grottoes (Xu, Zhou, and Li 1983; Joint Committee on Powder Diffraction Standards, n.d.). Fourteen of ninety-four pigment samples collected in the Tiantishan grottoes contained lead sulfate, which constitutes a major characteristic of the grotto. Basic sulfate and carbonate of lead, the natural mineral leadhillite (Zhou 1991); and lead hydroxychloride, $Pb(OH)_2 \cdot PbCl_2$, which is also the natural mineral laurionite, are two recently discovered natural white pigments used in ancient paintings.

Cinnabar and minium, and mixtures of cinnabar and lead white—or cinnabar, minium, and lead white (or other pigments containing lead)—were present in many red pigment samples. No signs of discoloration were seen.

The brown color found in Cave 3 was identified as a mixture of lead dioxide and minium. Lead dioxide is the oxidation product of minium.

Conclusions

In this work, the authors analyzed ninety-six samples in five caves of the Tiantishan grottoes and discovered that twenty-four different pigments were used (Table 1). These pigments have the following characteristics:

- Large amounts of white pigment containing lead were used; of these, laurionite and leadhillite were first discovered in this work.
- Many of the samples contained calcium oxalates.
- The green pigments were complex.
- Very few yellow pigments have survived in the polychrome statuary and wall paintings of these grottoes. In this work, the authors obtained only two such samples: no material exhibiting yellow coloration was seen in sample 24, and sample 96 was orpiment.

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Lead Isotope Analyses of Some Chinese and Central Asian Pigments

Robert H. Brill, Csilla Felker-Dennis, Hiroshi Shirahata, and Emile C. Joel

THE OBJECTIVE OF THIS ARTICLE is to encourage conservators of cave paintings and similar Buddhist works of art to take advantage of lead isotope analysis as an adjunct to other scientific investigations of pigments. Based on the exploratory findings reported here, it is expected that such analyses will prove helpful for classifying pigments and for learning more about their geographical origins. In a broader sense, these analyses might also serve as a prelude to a more general study of leads in Central Asian artifacts.

Lead isotope analyses can be carried out on very small samples of lead-containing materials because only microgram quantities of lead are needed. Even samples left over from other examinations, such as X-ray diffraction, are suitable for analysis. Thus, it is often possible to gain useful information without sacrificing additional samples of materials that have already been studied.

Lead Isotope Analysis

For these studies, lead is extracted from minute samples of any lead-containing material or artifact and is analyzed by mass spectrometry. The resulting isotope ratios are compared with ratios determined for other artifacts and for galena (lead sulfide) ores from ancient mining regions. Lead ores from different deposits can vary isotopically, depending on the geological ages of the deposits and the ore genesis. The objects analyzed can be classified by grouping those containing leads that might have a common geographical origin and separating those that contain leads from different mining regions. Judiciously interpreted, these findings offer valuable clues as to where the objects or materials themselves might have been made. In the most favorable instances, the actual mining regions from which the leads came can be identified.

Two complications of the method lie in overlapping and mixing. *Overlapping* refers to the fact that lead ores from different mining regions sometimes have very similar isotope ratios. *Mixing* means that when leads from different sources are recycled and melted together, the resulting

isotope ratios fall somewhere between those of the starting leads. Lead isotope ratios are not affected by the chemical history of the parent materials, providing that no contamination with lead from other sources is introduced. Unlike chemical compositions, which are greatly altered by the chemical reactions of processing, manufacturing, and weathering, lead isotope ratios determined today in ancient materials are exactly the same as they were in the original ores mined in antiquity.

Figure 1 summarizes the results of some twelve hundred ancient lead-containing materials, artifacts, and ores from a wide variety of places and times. The ellipses labeled L, M, E, J, and S are reminders of which isotopic ranges correspond—generally—to which sources of lead. L represents ores from the Laurion mines in Greece and artifacts of known Greek origins; M represents leads from Mesopotamia and some from Iran; E, English and certain European ores; J, some ores and artifacts from Japan; and S, leads from Spain, Wales, and Sardinia. Egyptian and Chinese leads are labeled accordingly. Recent research has established that lead isotope analyses are especially useful for studying Chinese and other Asian artifacts, including glasses, bronzes, Chinese blue and Chinese purple pigments, and glazes (Brill, Barnes, and Joel 1991; Brill and Shi et al. 1991; Yamasaki and Murozumi 1991; Brill 1993; Lee, Brill, and Fenn 1991; Brill and Vocke et al. 1991). As can be seen from the ellipses in Figure 1, numerous Chinese leads fall at the upper and lower extremes of the graph (although there are also many in the middle ranges). As more data are collected for ores in China and Central Asia, the locations of the mines that produced these leads should be identified (Brill and Chen 1991).

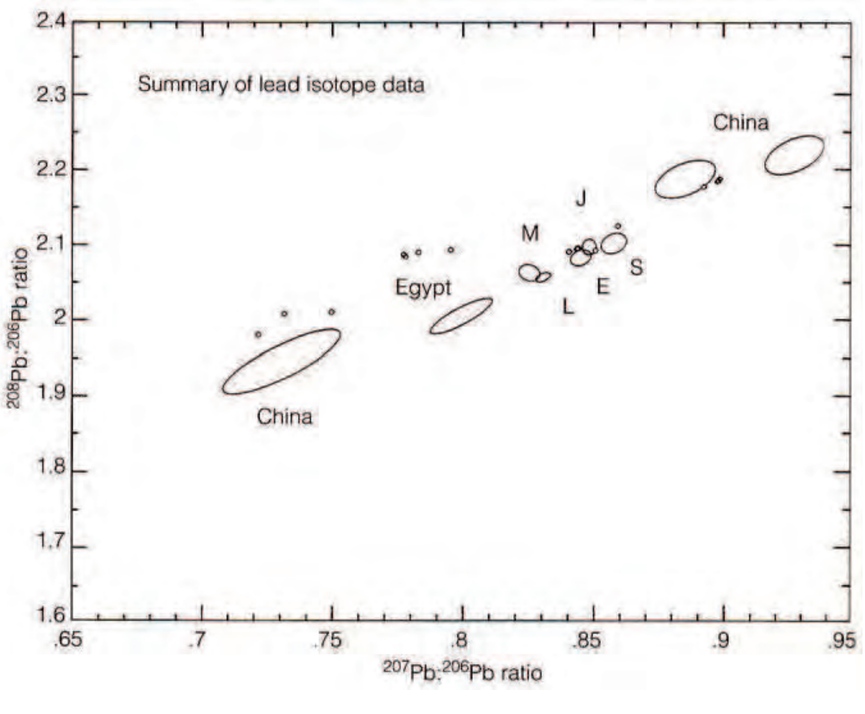

Figure 1
Summary of lead isotope data for approximately twelve hundred ancient artifacts and galena ores. Points represent samples in the present study. Data are assembled from various publications by one of the authors (RHB).

Lead Isotope Analyses of Some Buddhist Pigments

Lead isotope analyses should shed light on questions related to chronological or stylistic differences among Buddhist cave paintings and might distinguish between original and repainted parts of individual works. In this exploratory study, only seventeen pigments have been analyzed, but other analyses are already under way. The analyses were carried out in two laboratories. Some samples were analyzed by Hiroshi Shirahata and his coworkers at the Muroran Institute, while the others were analyzed at the National Institute of Standards and Technology by Emile C. Joel. The results are reported in Table 1 and plotted in Figures 1 and 2, along with the data for other relevant artifacts.

Seven samples from relief wall paintings presently in the Fogg Art Museum were analyzed first. The reliefs date from the Western Wei dynasty (535–557 C.E.) and originally came from two small caves at Tien Lung Shan in Shanxi Province. The pigments were investigated by Csilla Felker-Dennis while she was carrying out conservation examinations in 1982 (Felker and Dennis 1982). Several of the painted areas were found to contain lead in the form of plattnerite, PbO_2.[1] All seven samples measured less than 1 mm in their greatest dimension. Because they came from recessed parts of the carving, the samples were believed to represent original sixth-century painting, not later overpainting. Although black today, the pigment might well have originally been red lead (Pb_3O_4). An alternative hypothesis is that black plattnerite might have been a naturally occurring mineral.

Eight samples of red and white phases from extremely minute flakes of paint from Cave 6 at Yungang were also analyzed. These samples were left over from very comprehensive analyses of the original flakes of paint by Francesca Piqué, who provided the samples for the lead isotope analysis (Piqué herein).

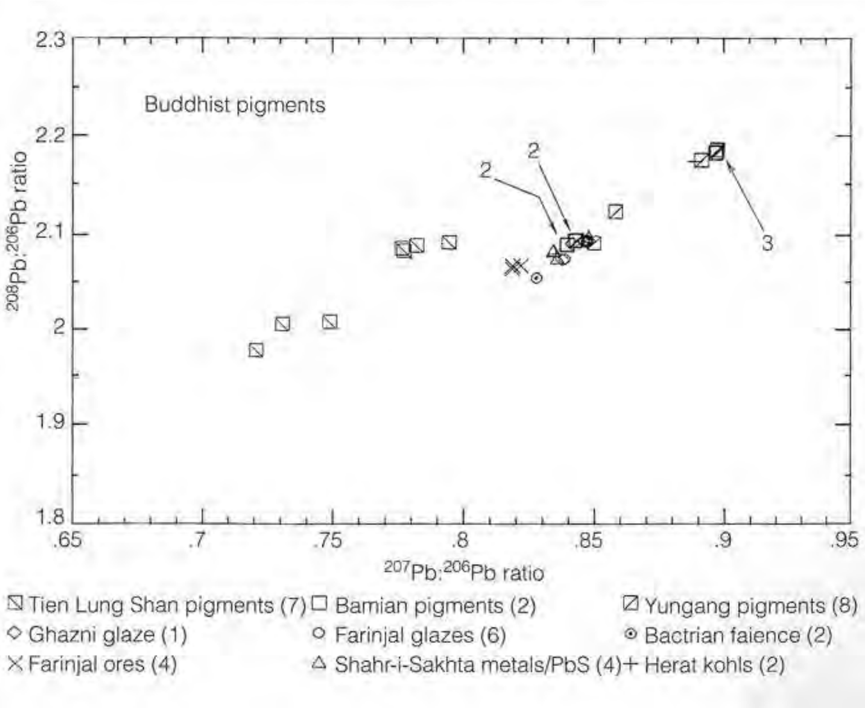

Figure 2
Lead isotope data for thirty-six samples in this study. Data are plotted as large symbols for greater legibility.

Table 1 Results of lead isotope analyses

Samples are listed in approximate ascending order of ^{207}Pb:^{206}Pb ratios.

Sample no.	Description	^{208}Pb:^{206}Pb	^{207}Pb:^{206}Pb	^{204}Pb:^{206}Pb	Lab
Pb-2034	Tien Lung, pigment	1.98001	0.72123	0.04429	NIST
2036	″ ″ ″	2.00771	0.73127	0.04512	″
2035	″ ″ ″	2.01000	0.74946	0.04650	″
2031	″ ″ ″	2.08636	0.77704	0.04858	″
2030	″ ″ ″	2.08372	0.77781	0.04871	″
2032	″ ″ ″	2.08925	0.78279	0.04900	″
2033	″ ″ ″	2.09243	0.79526	0.04997	″
Pb-839	Farinjal, ore	2.06763	0.81933	0.05210	Muro.
838	″ ″	2.06475	0.81935	0.05223	″
840	″ slag	2.06787	0.81950	0.05214	″
837	″ ore	2.06797	0.82250	0.05241	″
Pb-2054	Bactria, faience	2.05534	0.82857	0.05292	″
Pb-1430	Sh.-i-Sok., ingot	2.08146	0.83496	0.05333	″
1431	″ ″	2.08240	0.83514	0.05329	″
1433	″ Ag alloy	2.07408	0.83664	0.05341	″
Pb-1343	Herat, *sormah*	2.08020	0.83588	0.05328	NIST
Pb-841	Farinjal, glaze	2.07420	0.83865	0.05358	Muro.
847	″ ″	2.07506	0.83949	0.05365	″
Pb-2042	Bamian, pigment	2.08965	0.84040	0.05363	NIST
2043	″ ″	2.09013	0.84054	0.05346	″
Pb-1599	Ghazni, glaze	2.09117	0.84226	0.05362	″
Pb-2093	Yungang, pigment	2.09384	0.84341	0.05371	Muro.
2092	″ ″	2.09474	0.84409	0.05382	″
Pb-2055	Bactria, faience	2.09432	0.84705	0.05416	″
Pb-843	Farinjal, glaze	2.09270	0.84688	0.05398	″
846	″ ″	2.09277	0.84773	0.05428	″
842	″ ″	2.09495	0.84811	0.05420	″
845	″ ″	2.09261	0.84828	0.05405	″
Pb-1435	Sh.-i-Sok., galena	2.09679	0.84873	0.05437	″
Pb-2095	Yungang, pigment	2.09183	0.85061	0.05464	″
2099	″ ″	2.12422	0.85915	0.05508	″
Pb-867	Herat, *sormah*	2.17510	0.88955	0.05762	NIST
Pb-2094	Yungang, pigment	2.17641	0.89228	0.05784	Muro.
2097	″ ″	2.18364	0.89742	0.05828	″
2098	″ ″	2.18433	0.89788	0.05831	″
2096	″ ″	2.18689	0.89829	0.05824	″

Two other samples, collected by Brill in 1968, came from niches on the inside east wall near the top of the large Buddha at Bamian. Because of the complex nature of the material, and because some of the material was lost in the 1972 Corning flood, the exact nature of the pigments containing the lead are uncertain. Emission spectrography, X-ray fluorescence (XRF), and X-ray diffraction analyses had been carried out before the flood, along with certain microchemical spot tests. One sample apparently consisted primarily of crushed lapis lazuli and the other of a

red pigment, most likely cinnabar (HgS), but red lead could also have been present. Both samples contained a substantial level of lead, but its chemical form was uncertain, and the lead could have been in either a primary pigment or a white ground.

In addition, samples of other materials that might have a bearing on the interpretation of the pigment samples have also been analyzed. These include surface finds from the ancient metallurgical workings at Farinjal, Afghanistan (ores, slags, and lead-glazed pottery shards); blue glazes from two Bactrian faience beads; a glazed terra-cotta animal acquired in Ghazni; metals from Shahr-i-Sokhta; and, from Herat, two modern samples of galena, probably intended for use as the eye cosmetic *sormah*. Several copper-based alloy artifacts from Bamian and/or Chakhcharan are also now being analyzed.

Results of the Analyses

There are two noteworthy observations about the Tien Lung Shan pigments. First, although the seven leads were spread out over a wide isotopic range, all of them fall in the lower range of isotopic values. Three somewhat resemble the leads in the ellipse of Chinese glasses that anchors that corner of the graph in Figure 1. Among the other four samples, only two are isotopically quite similar, while the other two are nearby. Clearly, more than one source of lead is involved, and mixing has probably occurred. Beyond that, it is difficult to interpret the findings, because there does not appear to be any obvious correlation between the data and the locations from which the samples were taken within the cave. Perhaps some repainting is, after all, involved.

The Tien Lung Shan leads are a new type of lead to us. Except for the Chinese glasses, the authors know of no parallels. It is also worth noting that the pigments are displaced somewhat above the general trend of the Chinese data.

One useful inference can be drawn from the wide dispersion of the seven samples. If these pigments had been made from naturally occurring mineral deposits of plattnerite, they most likely would have come from a single, possibly local, deposit—but this is clearly not the case. Instead, the authors feel that the observed variability is more consistent with the view that this plattnerite is not a naturally occurring mineral, but that it is a weathering product of red lead, and that the red lead pigments are synthetic compounds prepared from leads that came from different places. Thus, the data suggest to us that the painted regions now containing black plattnerite were originally red.

The two Bamian pigments, one red and one blue, are virtually identical to one another isotopically, and are markedly different from the Tien Lung Shan pigments (Fig. 2). This is not surprising because the sites are located almost three thousand miles away from each other, but the data also indicate that their leads came from different geological settings.

The leads in the eight Yungang pigments are entirely different from the Tien Lung Shan pigments, and show some variability among themselves. Four of the samples lie in the upper right corner of the graph,

having very high isotope ratios. Their leads are similar, but not identical, to those in Warring-States and Han-dynasty Chinese glass eye-beads. Two other Yungang pigments (both red) are not very different from the Bamian pigments, while another—known, from dissection under the microscope, to contain a mixture of both red and white phases—lies between them. The Yungang pigments contain leads that clearly came from at least two different ore deposits.

This brings us, if only fortuitously, to a central point of this discussion. Although only a few samples have been run, they strikingly illustrate that a wide isotopic variability exists among these pigments. They spread over almost the entire range of isotope values encountered in more than twenty years of previous analyses. Seen from one point of view, this is encouraging: it establishes that marked differences exist among pigments from at least some sites, even though this is tempered by the fact that the Tien Lung Shan data alone show a great deal of variability. It remains to be seen whether the variability within other groups of related samples may be smaller (as it is with the two Bamian samples and some of the Yungang samples), so the method will produce the specificity needed to make it useful.

The only way to test for this usefulness is to analyze sets of carefully selected, well-studied, well-documented samples that may become available. That, as stated at the outset, was the principal aim of this writing and the presentation on which it was based: namely, to urge all those connected with research on Buddhist paintings to set aside samples for lead isotope analysis whenever possible.

Some Final Thoughts

Central Asia not only had, and has, its own indigenous cultures, but it also bears the imprints of contacts with innumerable other cultures, both neighboring and far distant. As people came, so also came goods, materials, and technologies. Lead isotope studies might someday be used as a complement to other kinds of evidence for tracing the origins of artifacts or materials that might otherwise remain in doubt. To attempt this, it is necessary first to see whether there is anything such as a Central Asian pattern of lead isotope ratios that might be distinguishable from, for example, the leads of Iran, China, India, and so on.

Unfortunately, limitations of space do not permit a discussion of the results of the initial twenty or so Central Asian artifacts mentioned here, but the data are included in Table 1 and plotted in Figures 2 and 3. Interested readers will be tempted to see a single Central Asian type of lead emerging near the center of Figure 2, but—plotted on an expanded scale, as in Figure 3—that "group" becomes resolved into perhaps as many as a half dozen different mining regions. Readers who are more interested still might like to discover for themselves some of the tantalizing similarities among groups and pairs of samples plotted in Figure 3. Only time, and a lot more data, will tell whether the picture can be clarified or whether—as has happened before—it will all become too entangled to unravel. In any event, that should not impede research on Buddhist pigments, because they

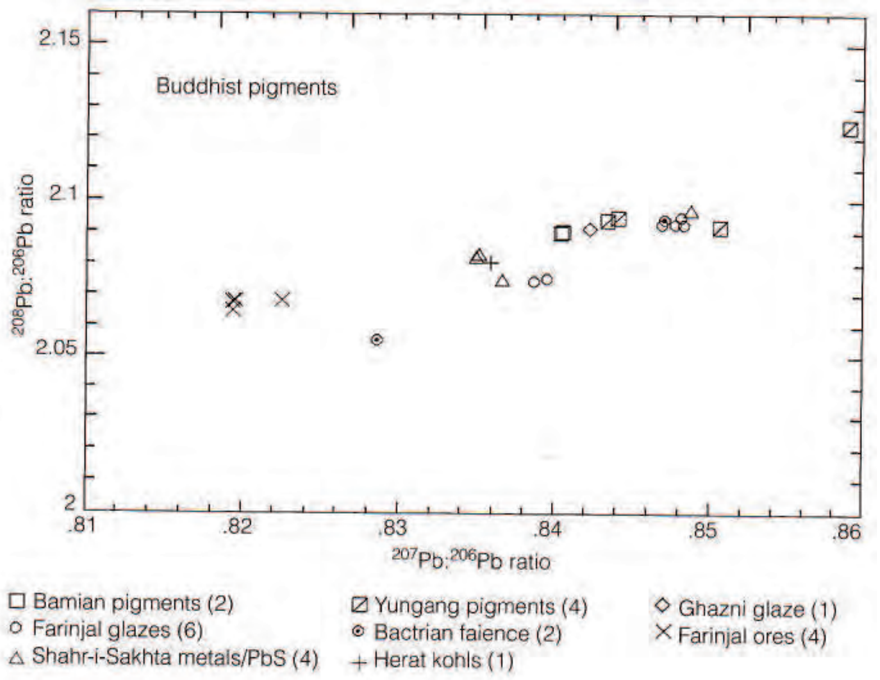

Figure 3
Expanded portion of Fig. 2. Data are plotted as large symbols for greater legibility.

can still be classified relative to one another in a self-contained way and may help art historians and archaeologists to establish connections between paintings found hundreds or even thousands of miles apart.

One of the authors (Shirahata) has recently completed analyses of twelve additional pigments from cave paintings. These are plotted in Figure 4, along with seventeen of the pigments plotted in Figure 2. Further details are available from the authors.

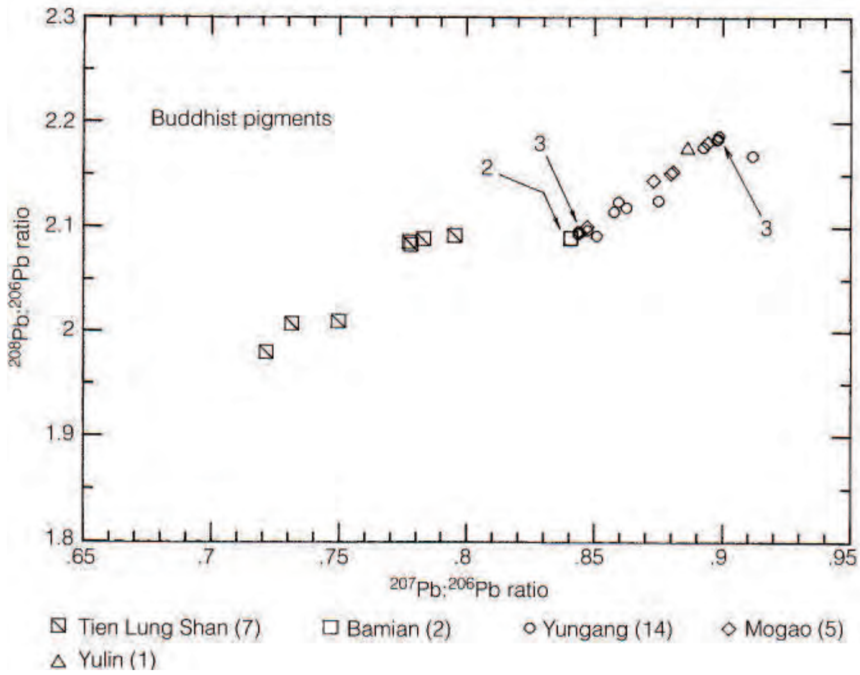

Figure 4
Data for twelve additional pigments from cave paintings (not described in text), along with replotted data for the seventeen pigments in Fig. 2.

Acknowledgments

Special thanks are extended to the individuals and institutions who provided the samples used in this study. They are identified in the sample description section at the end of this chapter. The authors also thank Kazuo Yamasaki, John Dennis, Eugene Farrell, Richard Newman, and Sherri Seavey for their contributions to this research. The diffraction patterns were run by Bryan R. Wheaton of Corning, Inc.; and the X-ray fluorescence by Philip M. Fenn of Corning, Inc., and George J. Reilly, then of the Winterthur Museum.

Note

1 The identification as plattnerite was made by one of the authors (CF-D), in collaboration with John Dennis. It was based on X-ray diffraction and microscopic examinations. At that time the name apsara black was suggested for the pigment. A straightforward calculation (by RHB) shows that the free energy of the reaction, as given here, is about $-40.50\ kJmol^{-1}$ (at 20 °C), indicating that the red-to-black transformation is thermodynamically favorable ($-40.50\ kJmol^{-1} = -9.68$ k cal. mol^{-1}):

$$Pb_3O_{4(c)} + O_{2(g)} \rightarrow 3PbO_{2(c)}$$

The free energy at 0 °C ($-44.27\ kJmol^{-1}$) is more negative than that at 35 °C ($-37.70\ kJmol^{-1}$), suggesting that the color change might tend to go faster in the winter than in summer, although that does not take into account catalysis or factors such as the presence of moisture that could also affect the mechanism and/or rate of reaction.

Sample Descriptions

Tien Lung Shan pigments

This group of samples came from painted stone reliefs now in the Fogg Art Museum. They are traces of pigments from low-relief paintings on the sandstone ceilings of Caves 2 and 3 at Tien Lung Shan in Shanxi Province. Six of the paintings depict apsaras in various attitudes and with various attributes. The seventh (Pb-2036) is a stela depicting the Buddha. All date from the Western Wei dynasty (535–557 C.E.).

Pb-2030	Flake of black pigment with white gypsum (?) ground. The pigment is now plattnerite, a black lead oxide (PbO_2). Cave 2, south. FAM no. 1943.53.9.
Pb-2031	As above. Cave 3, south. FAM no. 1943.53.10.
Pb-2032	As above. Cave 2, east. FAM no. 1943.53.12.
Pb-2033	As above. Cave 3, west. FAM no. 1943.53.14 (14/1).
Pb-2034	As above. Another sample (14/11).
Pb-2035	As above. Another sample (14/14).
Pb-2036	As above. Cave 3, Buddha figure in stone. FAM no. 1943.53.17.

Yungang, China, pigments

These samples were provided by Francesca Piqué. They are remains from analyses described in her article herein.

Pb-2092	Red pigment separated from Piqué no. 11.
Pb-2093	Red pigment separated from Piqué no. 21.
Pb-2094	White pigment separated from Piqué no. 35.
Pb-2095	White pigment separated from Piqué no. 37.
Pb-2096	Red pigment separated from Piqué no. 42.
Pb-2097	White pigment separated from Piqué no. 42.
Pb-2098	Black layer (with some white phases) separated from Piqué no. 44.
Pb-2099	Red pigment (with slight contamination of white phases) separated from Piqué no. 46.

Bamian pigments

Pb-2042	Blue pigment (powdered lapis lazuli) applied to grass-reinforced mud plaster. From wall painting in niche near top of large Buddha. Probably from seventh to ninth century. BAM-1. Collected by RHB on 6 August 1968. Sample contaminated with whitish ground (gypsum) and mud plaster.
Pb-2043	As above, red pigment. BAM-3.

Farinjal, Afghanistan, pigments

These pigments are from specimens collected by RHB on 6 August 1968 at site no. 4 of the National Geographic Society Metallurgical Expedition, headed by Theodore Wertime. This metallurgical site is thought to have been worked from 300 to 1200 C.E. Ore-bearing rock is present.

Pb-837	Mineral phase is black with fine-grained, lustrous crystals.
Pb-838	As above; a similar specimen.
Pb-839	As above; a similar specimen.
Pb-840	As above. Large nugget of vitreous slag. Black (v. dark olive).
Pb-841	As above. Pottery shard. Green glaze over white slip on salmon-colored body. 30–50% PbO.
Pb-842	As above. Bluish green glaze on salmon-colored body. 30–50% PbO.
Pb-843	As above. Green glaze on salmon-colored body. 1–3% PbO.
Pb-845	As above. White glaze on thick buff-colored body. 30–50% PbO.
Pb-846	As above. Rim fragment. White glaze with dark blue, linear, cloudlike decoration on soft, light-gray body. Probably made in Iran in imitation of Chinese porcelain. Said by D. B. Whitehouse to be of a type commonly found near Kandahar. 0.03–0.1% PbO.
Pb-847	As above. Body fragment. White glaze on one surface, mainly dark blue (with some white) on other. Probably made in Iran in imitation of Chinese porcelain. 0.01-0.03% PbO.

Shahr-i-Sokhta, Iran, pigments

The following samples were submitted by Maurizio Tosi of the Istituto Universitario Orientale, Naples, on 29 June 1977.

Pb-1430	Pan-shaped ingot, from bottom of a melting crucible, ca. 2500 B.C.E. XRF gives 75% Pb, no Cu or Sn.
Pb-1431	As above; a similar ingot. XRF gives 75% Pb, no Cu or Sn.
Pb-1433	As above. A stamp seal; 2500–2000 B.C.E.
Pb-1435	As above. A piece of galena; 2200–1800 B.C.E. Square RWJ(L).

Other pigment samples

Pb-1599	Glazed terra-cotta figure of an animal; date uncertain. Purchased in Ghazni by Robert H. Brill on 10 August 1968. Sample is of green lead glaze.
Pb-2054	Faience bead in the shape of a duck. Bactria. Ancient but of uncertain date. Whitish, porous, fine-grained body with remains of greenish-blue glaze. From same group as CMG 93.7.1. Sample consists of glaze with much body material. PbO ~ 0.08% in glaze.
Pb-2055	An incurved biconical bead, with perforated bore (not of the hollow nutshell type). Bactria. Whitish, porous, fine-grained body with remains of blue glaze. From same group as CMG 93.7.1. Sample consists of glaze with much body material. PbO ~ 0.03% in glaze (related to sample Pb-2054).
Pb-867	Herat, Afghanistan. Nugget of galena purchased in the potters' bazaar. Possibly for use as *sormah,* an eye cosmetic. See Brill's field notes for 2 July 1972.
Pb-1343	Herat, Afghanistan. Said to be from Chakhcharan. Galena, possibly for use as *sormah,* an eye cosmetic (related to sample Pb-867). See Brill's field notes for 15 September 1977.

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Formation and Stability of Chinese Barium Copper–Silicate Pigments

Hans G. Wiedemann and Gerhard Bayer

Blue and purple pigments were used in ancient China for decorating pottery and metallic objects and for wall paintings. They were also produced in the form of octagonal sticks. The use of such pigments was common, especially during the Han dynasty (208 B.C.E.–220 C.E.). West FitzHugh and Zycherman (1983, 1992) showed that these pigments are barium copper silicates of defined, specific composition. This report primarily addresses the two Chinese pigments, Han blue ($BaCuSi_4O_{10}$) and Han purple ($BaCuSi_2O_6$).

Han blue has the identical structure and crystal habit as Egyptian blue ($CaCuSi_4O_{10}$) (Pabst 1959; Chase 1971; Bayer and Wiedemann 1976), a calcium copper silicate produced and used extensively in ancient Egypt beginning around 3000 B.C.E. Previous investigations of the formation and stability of Egyptian blue and its strontium and barium analogues showed that the barium copper silicate is thermally much more stable than Egyptian blue. Compared to the system CaO-CuO-SiO_2, the corresponding system with BaO is more complex. At least four ternary barium copper silicates have been found to exist (JCPDS files; Finger, Hazen, and Hemley 1989): $BaCuSi_4O_{10}$ (Han blue), $BaCuSi_2O_6$ (Han purple), $BaCu_2Si_2O_7$ (another blue), $Ba_2CuSi_2O_7$ (another blue). Synthesis of the pure phases is not straightforward; usually a mixture of compounds is formed initially, depending on the raw materials used, their ratio, the addition of fluxes, and the temperature and time of reaction.

The role of the barium minerals is of special interest. China has a long history and tradition of developing and utilizing ores and minerals. It is likely that copper sulfides were used together with barite and silica sand or quartzite to make the pigments. Barite ($BaSO_4$) is found in a variety of deposits all over China. Witherite ($BaCO_3$), which is sometimes associated with barite, is much rarer. The raw materials for the blue and purple barium copper–silicate pigments used in the Mogao grottoes probably came from copper deposits in Gansu Province, such as those near Lanzhou, Gulang, or Jiayuguan (Gloria, Harrison, and Braumann 1985).

Synthesis of the barium copper–silicate pigments requires specific conditions with respect to heat treatment and flux addition, depending on

the raw materials used. The investigations reported here focused primarily on the effect of the barium minerals on the formation of the blue and purple pigments. For these experiments copper was added as an oxide since any copper sulfide will be oxidized to CuO well below the temperature where the reaction starts (Bayer and Wiedemann 1992). The reaction rate was accelerated by the addition of fluxes such as NaCl and Na_2CO_3. Additional investigations concerned the chemical and thermal stability of the various pigment samples.

Experimental Approach

All the barium copper silicates were prepared by solid-state reaction in air between the corresponding oxides in the temperature range of 900–1100 °C. The raw materials, chemically pure and finer than 40 μ, were $BaSO_4$, $BaCO_3$, CuO, Cu_2S, and SiO_2. They were homogeneously mixed, compacted slightly, and heated for approximately twenty hours.

The crystalline reaction products were identified by X-ray diffraction (Guinier de Wolff camera, CuK-alpha radiation). This proved difficult when a mixture of the various barium copper silicates was present in the samples along with barium silicates and unreacted starting materials.

The Mettler Thermoanalyzer TAl was used for simultaneous thermogravimetry (TG) and differential thermal analysis (DTA). In addition, the Mettler Toledo System TA 8000/TG 850 was used for TG, especially in a controlled atmosphere. The heating rates varied between 2 °C min^{-1} and 10 °C min^{-1}. Platinum and alumina crucibles were used because of their high thermal conductivity, which is important for the DTA runs. Otherwise, any ceramic container can be used for the synthesis of the pigments; in the authors' experience, it has no effect on the color.

Results and Discussion

Synthesis by solid-state reaction was carried out to understand the formation of the different colors of barium copper–silicate pigments. Previous studies of Han blue ($BaCuSi_4O_{10}$) showed that not only temperature but also the barium compound used and the fluxes added (Bayer and Wiedemann 1976) have a distinct effect on the color tone of this pigment.

For the present work, mixtures of different stoichiometry were prepared, using only $BaCO_3$ and $BaSO_4$ to simulate the preparation of the blue and purple pigments with naturally occurring raw materials. Other barium compounds are more reactive; however, it is highly unlikely that they were used in ancient China.

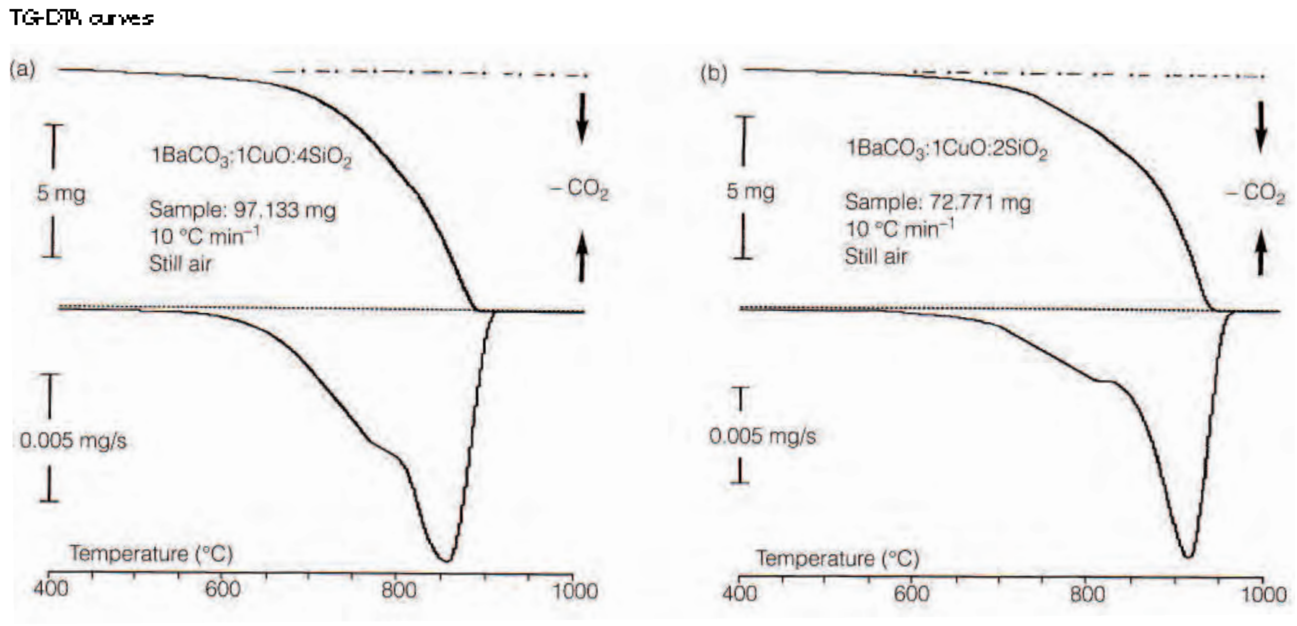
Fluxes posed a particular problem. Their addition had a definite effect on the formation and color of the resulting pigment. It was found that the addition of more than 5% Na_2CO_3, and heating to above 1000 °C, resulted in melting of the Han purple compound to a glass. Han blue was more stable. There were other side reactions from the fluxes. In starting mixtures with $BaCO_3$ as the barium source, the addition of Na_2SO_4 caused the intermediate formation of $BaSO_4$ in the temperature range of 600–800 °C. This was due to the displacement reaction $BaCO_3 + Na_2SO_4 \rightarrow BaSO_4 + Na_2CO_3$ (Bayer and Wiedemann 1987). Since there is a pronounced

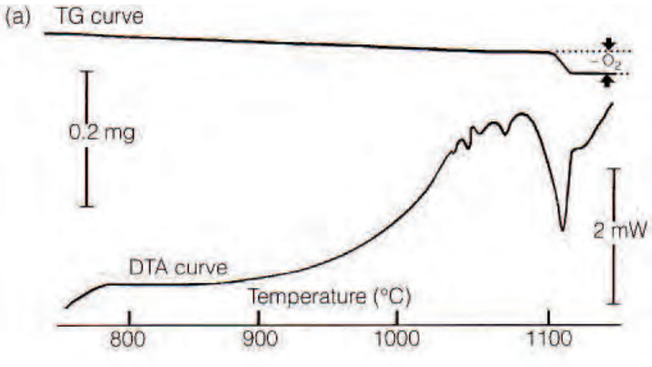
difference between the reaction behavior of $BaCO_3$ and $BaSO_4$ in the formation of the pigments, the influence of the flux components in the reaction must also be taken into account. Because the original Han purple pigment contained a high proportion of lead oxide, this was also tried as a flux. It was very effective in the formation of both Han purple and Han blue at 900 °C. However, adding more than 5% lead oxide led to partial melting and glass formation above 1000 °C. This agreed with the macroscopic appearance of the obviously partially vitrified purple octagonal sticks (West FitzHugh and Zycherman 1983, 1992).

Synthesis of Han purple and Han blue with $BaCO_3$

To synthesize the purple and blue pigments, mixtures of $BaCO_3$, CuO, and quartz powder were prepared with the following stoichiometric ratios: 1:1:2, 1:1:4, 1:2:2, and 2:1:2. The mixtures were placed in porcelain crucibles, compacted slightly, and heated in air to 900, 1000, and 1100 °C. A flux of 3% Na_2CO_3, or 5% PbO, or 10% NaCl was added to some of these mixtures. TG and DTA runs were carried out with the 1:1:2 and 1:1:4 mixtures. They showed that in the presence of SiO_2, the decomposition of $BaCO_3$ starts below its phase transition at around 800 °C. The decomposition to BaO + CO_2 proceeds faster above this temperature and is complete at about 950 °C (Fig. 1). The solid-state reaction leading to barium copper silicates probably starts around 900 °C. Partial melting and reduction $Cu^{2+} \rightarrow Cu^{1+}$ occur at temperatures above 1050 °C depending on the BaO:CuO:SiO_2 ratio (Fig. 2). Han purple ($BaCuSi_2O_6$) is formed as the primary barium copper silicate in mixtures with the 1:1:4 stoichiometry. It is thermally less stable than Han blue ($BaCuSi_4O_{10}$) and melts with decomposition around 1100 °C. Pure Han blue could be synthesized more easily with the addition of fluxes such as Na_2CO_3 or borax. Section A of Table 1 shows some of the syntheses carried out with $BaCO_3$ and the various phases that formed. The latter were identified by X-ray diffraction.

Figure 1
Thermogravimetry (TG) and differential thermal analysis (DTA) curves of $BaCO_3$-CuO-SiO_2 mixtures heated to 1000 °C for the synthesis of Han blue and Han purple.





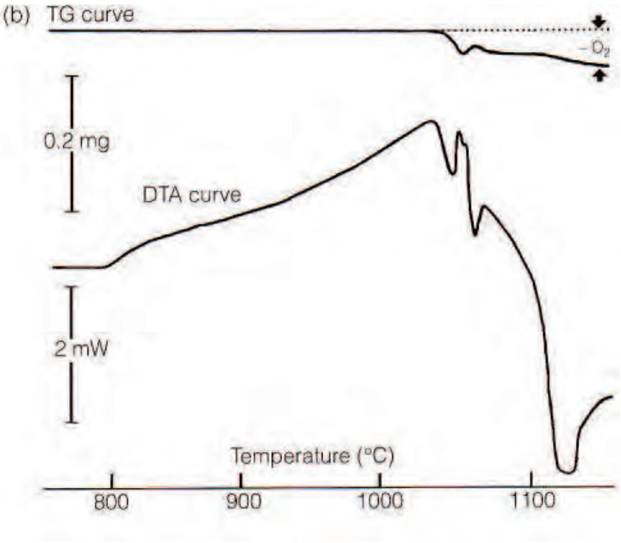


Figure 2
TG and DTA curves of pre-reacted mixtures shown in Figure 1 after additional heating.

Table 1 Synthesis of barium copper–silicate pigments (X-ray diffraction results)

	Reaction products after heat treatment	
Sample mixture	1000 °C, 20 h	1100 °C, 20 h
(A) With $BaCO_3$		
$BaCO_3$, CuO, SiO_2 1:1:2	$BaCuSi_2O_6$ (m) $BaCu_2Si_2O_7$ (w) blue-purple	$BaCuSi_2O_6$ (s) purple
$BaCO_3$, CuO, SiO_2 1:1:2 +3% Na_2CO_3	$BaCuSi_2O_6$ (w) ? (w) purple	$BaCuSi_2O_6$ (s) purple
$BaCO_3$, CuO, SiO_2 1:1:2 +5% PbO	$BaCuSi_2O_6$ (s) $BaCuSi_4O_{10}$ (w) purple-blue	
$BaCO_3$, CuO, SiO_2 1:1:4	$BaCuSi_2O_6$ (s) $BaCuSi_4O_{10}$ (m) bluish-purple	$BaCuSi_4O_{10}$ (s) $BaCuSi_2O_6$ (vw) blue
$BaCO_3$, CuO, SiO_2 1:1:4 +3% Na_2CO_3	$BaCuSi_4O_{10}$ (s) $BaCuSi_2O_6$ (m) blue	$BaCuSi_4O_{10}$ (s) blue
(B) With $BaSO_4$		
$BaSO_4$, CuO, SiO_2 1:1:2	$BaCuSi_4O_{10}$ (m) $BaSO_4$ (m) CuO (vw) bluish-gray	$BaCuSi_4O_{10}$ (s) $BaSO_4$ (m) $BaCuSi_2O_6$ (m) purple-blue
$BaSO_4$, CuO, SiO_2 1:1:2 +3% Na_2CO_3	$BaCuSi_4O_{10}$ (s) $BaSO_4$ (m) bluish-gray	$BaCuSi_4O_{10}$ (m) $BaCuSi_2O_6$ (s) $BaSO_4$ (w) purple-blue
$BaSO_4$, CuO, SiO_2 1:1:2	$BaCuSi_4O_{10}$ (m) $BaSO_4$ (m) CuO (w) greenish-blue	$BaCuSi_4O_{10}$ (s) $BaSO_4$ (w) blue
$BaSO_4$, CuO, SiO_2 1:1:4 +3% Na_2CO_3	$BaCuSi_2O_6$ (s) $BaSO_4$ (m) bluish-purple	$BaCuSi_4O_{10}$ (s) blue

vw = very weak w = weak m = medium s = strong v = very strong

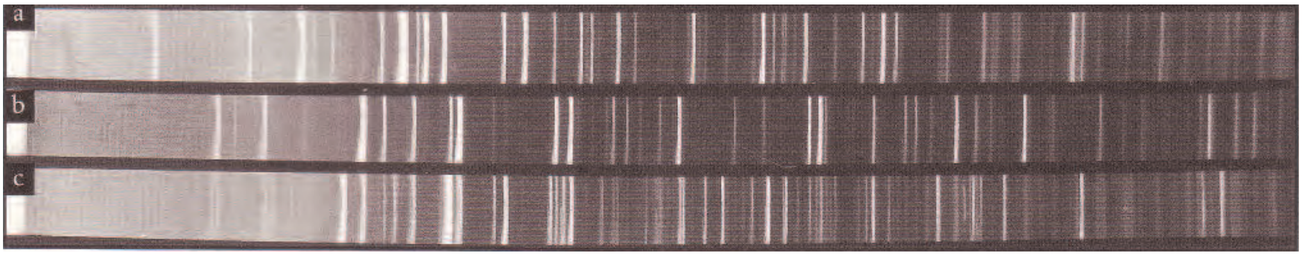


Figure 3
X-ray-diffraction powder patterns of barium copper–silicate pigments, top to bottom: (a) Han blue, (b) Han purple, and (c) $BaCu_2Si_2O_7$ (another blue).

The formation of colorless barium metasilicate as a primary phase was observed in several mixtures. Most of the $BaCO_3$:CuO:SiO_2 mixtures showed the presence of both purple and blue barium copper silicate, especially when heated to around 1000 °C. Pure Han purple was easier to synthesize than pure Han blue. The kind of flux added to the starting mixture, which contained the highly reactive $BaCO_3$, had a strong effect on the resulting color tone, which could be pure purple, pure blue, or a mixture of both. The addition of NaCl caused volatilization of some copper as $CuCl_2$ which is oxidized to CuO in the cooler zone of the furnace. Fluxes such as Na_2CO_3, PbO, or borax did not cause problems. When heating mixtures in which copper sulfides were used, their oxidation led to the evolution of SO_2, which reacted with $BaCO_3$ to form $BaSO_4$. This caused changes in the color tone compared to a mixture of identical stoichiometry where CuO was used instead of Cu_2S. The X-ray-diffraction powder patterns of pure Han purple (1:1:2) and Han blue (1:1:4) are shown in Figure 3.

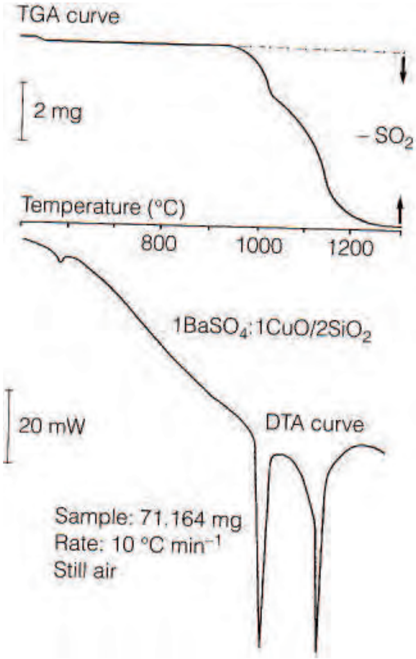


Figure 4
TG and DTA curves of the $BaSO_4$-CuO-SiO_2 mixture for the synthesis of Han purple.

Synthesis of Han purple and Han blue with $BaSO_4$

For these syntheses, the same procedure used for mixtures containing $BaCO_3$ was followed. TG and DTA runs showed that $BaSO_4$ has a higher thermal stability than $BaCO_3$ and starts to decompose slowly above 950 °C (Fig. 4). Even after heating for twenty hours at 1100 °C, a large amount of $BaSO_4$ remained unreacted. Consequently, the proportion of the Han purple and Han blue reaction products ($BaCuSi_2O_6$ and $BaCuSi_4O_{10}$) differed from the proportion found in corresponding mixtures with $BaCO_3$; hence the color tone also differed. Section B of Table 1 shows some of the syntheses carried out with $BaSO_4$.

The slower decomposition rate of $BaSO_4$, and thus the smaller amount of BaO available for reaction, obviously favored the primary formation of the more silica-rich Han blue. In addition, for the mixture ratio 1:1:2, Han blue continued to persist along with Han purple even at 1100 °C. This is in contrast to the corresponding mixtures with $BaCO_3$, where the formation of Han purple was strongly favored over Han blue, and where reactions generally started at lower temperatures. Mixtures with a 1:1:2 ratio melted to a homogeneous black glass above 1,300 °C and formed thin slabs from around 1,500 °C. Cooling this glass melt slowly in the crucible resulted in a blue-purple reoxidized material containing Han blue and Han purple as crystalline phases (Fig. 5). Reheating of the quenched glass to 950 °C led to crystallization of Han blue in a

powdered sample, and crystallization of Han blue, Han purple, and $BaSi_2O_5$ in bulk samples. This difference in recrystallization was due to surface-dependent nucleation.

Thermal and Chemical Stability of Han Purple and Han Blue

Figure 5
Blue-purple pigment mixture recrystallized during cooling of glass melt.

Han purple and Han blue are closely related structurally (Pabst 1959; Finger, Hazen, and Hemley 1989). Both show the identical square, four-fold coordination for Cu^{2+} and SiO_4^- tetrahedra that are linked to four-membered rings. These rings are isolated in the structure of Han purple but linked to four others in the adjacent layer in Han blue. This leads to the formation of a unique, four-ring, silicate-layer structure for Han blue and a different kind of barium-oxygen coordination. The continuous, zigzag, four-ring layers parallel to the (001) crystal face probably lead to better shielding of the barium and copper ions, and may be responsible for the higher thermal and chemical stability of Han blue over Han purple.

The phase diagram for the BaO-CuO-SiO_2 system is not yet known. However, both Han purple and Han blue lie on the straight line that runs from $BaCuO_2$ to SiO_2. Therefore, the more silica-rich Han blue ($BaCuSi_4O_{10}$) should have a higher melting point than Han purple ($BaCuSi_2O_6$). This was confirmed by the isothermal heat treatment of corresponding samples at 1200 °C for four hours. Pure Han purple (1:1:2) melted to a viscous, black-green glass, whereas Han blue (1:1:4) only showed increased sintering. X-ray investigation of these samples quenched from 1200 °C proved that the former was amorphous and vitreous, while the latter was unchanged $BaCuSi_4O_{10}$ (Han blue).

The striking difference in chemical stability between the purple and blue pigments has already been stressed by Pabst (1959) and by West FitzHugh and Zycherman (1983), and was confirmed by the authors' experiments. Blue $BaCuSi_4O_{10}$ was completely stable in dilute acids while purple $BaCuSi_2O_6$ faded rapidly and decomposed. The same effect was found when the purple pigment was treated with aqueous oxalic acid. It has been documented that lichens, which excrete oxalates or even oxalic acid, play a role in the deterioration of works of art (Seaward and Giacobini 1989). The turquoise-bluish residue formed by the reaction of Han purple with oxalic acid was identified as the double oxalate $BaCu(C_2O_4)2 \cdot 6H_2O$. Its decomposition to CuO + $BaCO_3$ can be seen from the TG curve shown in Figure 6. Below 250 °C there is a certain similarity to the decomposition of oxalic acid with H_2O, CO, and CO_2 given off. The peaks at higher temperature probably result from the decomposition of intermediate, basic copper carbonates. Additional experiments showed that Han purple also decomposes gradually in an atmosphere containing SO_2.

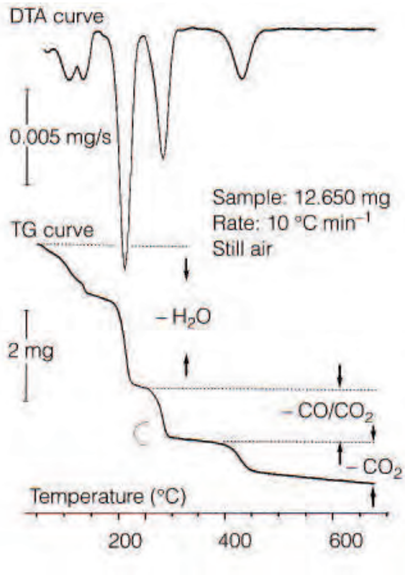


Figure 6
TG and DTA curves of the reaction product from Han purple and oxalic acid.

It was possible to analyze a tiny sample of original Han purple and to compare its composition to that of the synthetic purple pigment (Fig. 7). The excess silica and high lead concentration in the original sample was striking; these materials were obviously added as a flux or sintering aid. To the authors' knowledge, lead isotope analysis has not been performed on the Han purple sticks.

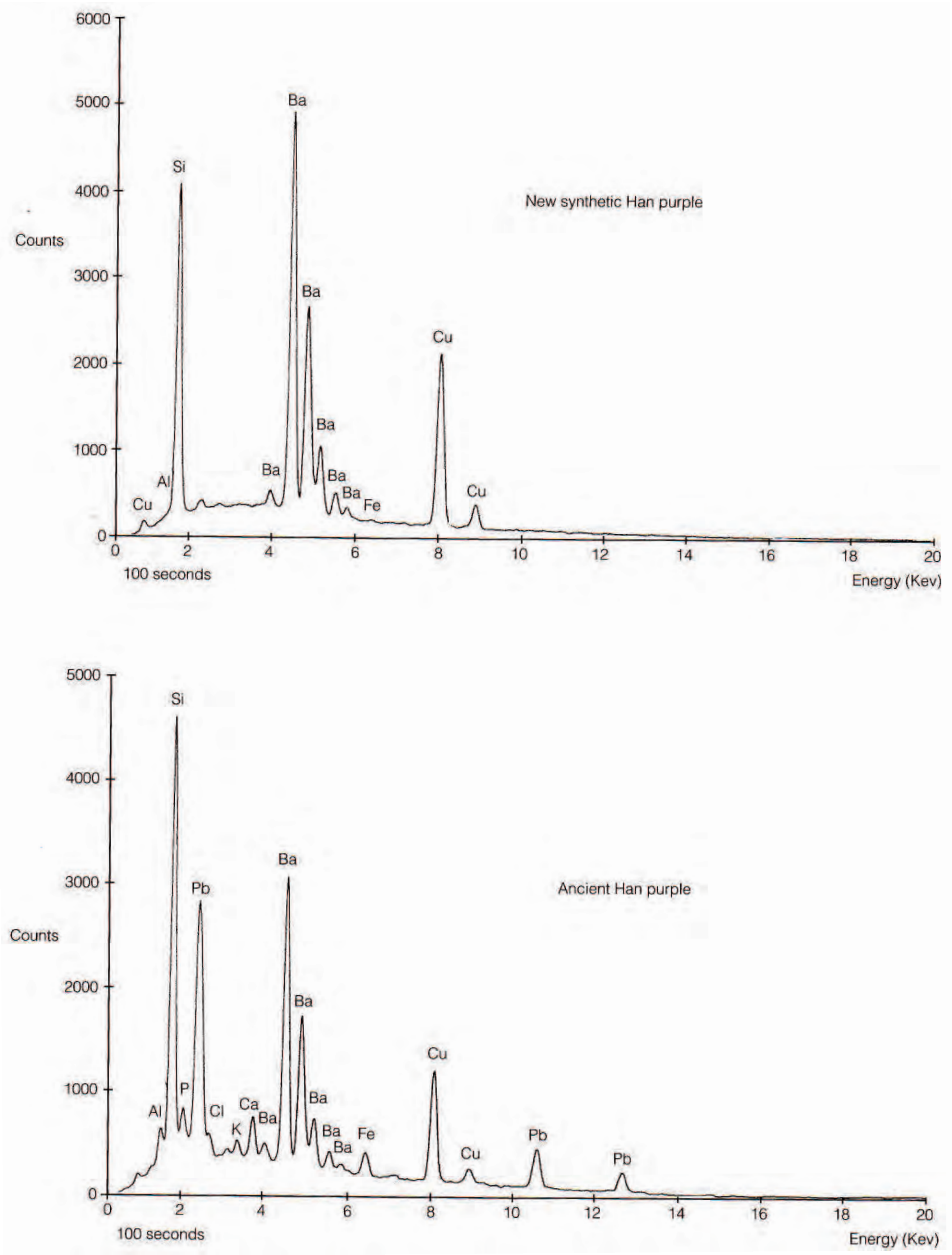


Figure 7

Energy-dispersive X-ray analysis curves of synthetic and ancient Han purple.

Effect of Pigments on the Conservation of Objects

In previous investigations of colored Egyptian papyri, spores and fungi were not observed in areas where Egyptian blue ($CaCuSi_4O_{10}$) was used as pigment. These findings were confirmed by further studies of different papyri. It was therefore assumed that copper-containing compounds had some effect on inhibiting the growth of mold, fungi, and lichens. Experiments with lichen-covered limestone proved this; no further growth occurred in areas where the lichens were removed and the exposed limestone was subsequently painted with Egyptian blue.

It is interesting that the production of "blue bread" is mentioned in documents of the Eighteenth Dynasty (1500 B.C.E.) in ancient Egypt (Sethe 1961). Since the Egyptians produced air-dried bread for emergency situations, it may be that they had some knowledge about the conservation effect of the Egyptian blue pigment. Likewise, it is possible that Han blue and/or Han purple may have similar fungicidal properties as Egyptian blue. Experiments to examine this have begun. A thermomicrobalance and hot-stage microscope are being used to obtain detailed insight into the growth and life cycle of lichens that attack artifacts. This setup makes it possible to correlate weight changes with macroscopic and microscopic changes in the artifacts as a function of different atmospheres and temperatures. The results are important to the understanding of how chemical environment affects the growth and life cycle of lichens, and could lead to new ways of protecting objects from deterioration.

Summary

Experimental investigations were carried out on the synthesis of barium copper–silicate pigments by means of solid-state reactions. It was shown that the main factors that control the color tone of the different purple and blue pigments are kind and purity of raw materials used, mixture ratio, nature of the flux used, heating, and temperature. There was a pronounced difference in reaction behavior between $BaCO_3$ and $BaSO_4$ as starting materials; generally the carbonate reacted much faster and at lower temperature than the sulfate. Han purple ($BaCuSi_2O_6$) was easier to obtain in pure form than Han blue ($BaCuSi_4O_{10}$), unless special fluxes were added. Depending on their chemical composition, the fluxes would react with the raw materials, and this also had an effect on pigment color.

Han blue was thermally and chemically much more stable than Han purple. Heating to 1200 °C did not change blue $BaCuSi_4O_{10}$, while purple $BaCuSi_2O_6$ completely melted to a black glass just below 1100 °C. This glass could be recrystallized to Han purple at about 900 °C. The poor resistance of Han purple to acids (including oxalic acid) resulted in rapid fading and decomposition. This is in striking contrast to the completely stable Han blue. This is probably due to the different coordination of Ba^{2+} and the arrangement of the Si_4O_{10} rings in the structures of these compounds.

In conclusion, the results of these investigations may contribute to a better appreciation of the early Chinese methods of manufacturing Han blue and Han purple pigments, and lead to an explanation for the variety of color tones observed.

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The Polychrome Terra-cotta Army of the First Emperor Qin Shi Huang

Wu Y. Onggi, Zhou Tie, Zhang Zhijun, Erwin Emmerling, and Cristina Thieme

In July 1974, the excavation of one of the most spectacular archaeological finds of this century began: the Terra-cotta Army of the Emperor consists of more than seven thousand life-sized clay soldiers, six hundred clay horses, one hundred wooden wagons, and thousands of bronze weapons. Most of the clay soldiers are broken. Thousands of shards in all sizes probably date from as early as 206 B.C.E., after the fall of the Qin dynasty, as a rebel army pillaged the grounds, and then later as the wooden roofs above the passages collapsed (Qu and Cheng et al. 1984).

In addition to the difficulties of excavation, conservation of the existing remnants of paint layers covering the figures at the Museum of the Terra-cotta Army, Lintong, Shaanxi, is one of the main concerns of a collaborative project between the Ministry for Cultural Properties of the Province of Shaanxi and the Bavarian State Conservation Office. The entire army of figures was originally painted in color (Fig. 1). Since the clay fragments dry out after being excavated, remnants of their paint layers are always extremely vulnerable and likely to fall off. To develop suitable methods of conserving these endangered paint layers, excavation work on the figures of the Terra-cotta Army was stopped several years ago.

Figure 1
Clay figure with remnants of the paint layer.

Since June 1991, the restoration ateliers of the Bavarian State Conservation Office have been investigating the paint materials, painting techniques and the state of preservation of the polychromy of the army of clay figures. For conservation techniques to be successful, knowledge and correct judgment of the aging phenomena and the causes of damage are fundamental. The first steps to approaching such questions consist of exact determination of the structure of the paint layers and their state of preservation; and research into the composition of the materials, material properties, and the techniques used to manufacture the clay figures and apply the polychromy. Of special importance is information on how the painting materials withstand extreme changes in climate, as are unavoidable during excavation (Thieme et al. 1993:6–54), when the clay figures are brought from wet burial conditions into dry surrounding air.

Manufacturing Techniques for the Terra-cotta Figures

Most of the clay figures are made of a gray terra-cotta, and some of red terra-cotta. The clay figures consist of separate body parts that can be fitted together. The individual parts—torsos, legs, and arms—are built up out of clay coils; other parts were made with the help of molds—negative forms into which the soft clay was pressed to achieve the desired form. Molds were not used to make all the individual parts but were the basic means of standardizing and accelerating production (Ledderose et al. 1990). All fragments are made of very high-quality clay and have been excellently preserved. The tremendous weight of the clay figures (about 200 kg) causes a considerable problem and requires measures to provide physical support, such as textile fabric that is glued onto the inside of the figures to prevent the glued cracks from opening up again.

Painting Techniques and Materials: Construction of the Paint Layers

The top layer of paint that covers the figures completely has a matte surface today. In general, the paint layers consist of a single or double layer of dark brown ground made of organic materials, and of pigmented layers that vary in number and thickness.

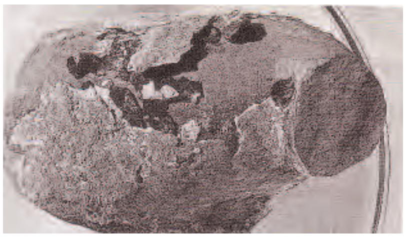

Figure 2
Fragment 003-1991 at 84% RH, maximum length 6.5 cm. Incarnate layer (pit 3 – N0264).

Figure 3
Detail of Fig. 2. On the gray terra-cotta is a double layer of dark brown ground made of organic materials (oriental lacquer tree, *Toxicondendron verniciflua*). The rose-colored pigment layer covering the ground layer has soil materials on the surface.

Ground layers

Chemical analysis of the binding medium shows that the main component of both ground layers is the sap of the oriental lacquer tree, the *Toxicodendron vernicifera.* The dark brown ground clearly reacts differently than other oriental lacquers and develops extreme tension during absorption of moisture. This behavior is very similar to that of a layer of glue or a mixture of glue and gum. The ground, however, also demonstrates chemical resistance to organic solvents that is typical of oriental lacquer. Admixtures such as glue or gum might be present in the lacquer but could not be detected by means of infrared (IR) spectroscopy and gas chromatography mass spectrometry (GCMS).

In color, the ground of all the fragments examined in Munich ranges from brown to dark brown. The double-layered ground is applied in two thin layers (total thickness approximately 0.1 mm) and consists only of the binding medium (Figs. 2, 3). The double-layered ground is extremely sensitive to variations in humidity and loses considerable volume during drying, results of which are visible as drastic craquelure and strong buckling of the flakes thus formed.

The single-layered ground is brown, transparent, and extremely thin. In a dry state, it exhibits microcracks. In contrast to the double-layered ground, the single-layered ground is stable with respect to changes in climate and does not pose any conservation problems. The research methods used were infrared spectroscopy, microhydropyrolysis, and microchemistry (Herm 1991).

Pigmented layers

The colored layers differ in number, thickness, and the mixture of pigments used. So far, the only binding medium detected has been oriental lacquer. This seems an unlikely binding medium to use in the pigmented

layers, but it was not possible to determine whether another binding medium was used as well.

The optical and physical characteristics exhibited by the paint layers of the clay figures today are similar to the properties of paint with glue as the binding medium. The assumption that this is not a pure lacquer technique is also based on technical observations of the paint properties. The pigments used are not resistant to lacquer. The flesh-colored paint layers consist primarily of bone white, a pigment that turns brown when bound with oriental lacquer. It is still unknown whether typical Chinese painting techniques were used or whether a technique was used that is unique to the Qin figures. Descriptions of painting layers that exhibit similar behavior and produce similar conservation problems after excavation have not been found in the literature.

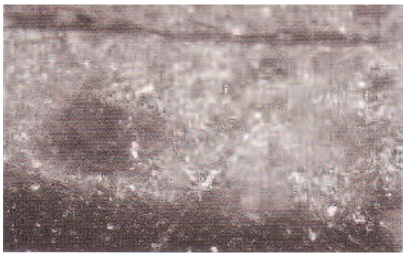

Figure 4
Fragment 003-1992. Cross section of the purple paint layer. Barium copper silicate mixed with cinnabar, ×780.

A typical characteristic of all the flesh-colored paint layers examined is their extreme thickness (0.10–0.20 mm). Identified pigments are bone white, $Ca_5(PO_4)_3OH$, and cinnabar. All examined intact sections of the clay soldiers contain hydroxyapatite, $Ca_5(PO_4)_3OH$. This pigment is manufactured by heating bone to 1000 °C. In contrast to the flesh-colored layers, the red areas are thinly painted. Identified pigments are cinnabar, green, and blue; detected pigments are malachite and azurite. The violet paint is composed of cinnabar and barium copper silicate, $BaCuSi_2O_6$ (Fig. 4). A violet pigment with identical composition was recently detected for the first time by West FitzHugh and Zycherman (1992). The research methods used were X-ray diffractometry (XRD), energy dispersive X-ray fluoresence (EDX), and scanning electron microscopy (SEM-EDX) (Herm 1991).

Damage to the Paint Layers

Visible reactions first occur when the fragments start to dry. The form of damage to the polychrome fragments cannot be generalized. Different kinds of polychromy show clearly differentiated characteristics of paint layers and also different manifestations of damage. These depend on the number of ground layers and the thickness of the colored paint layers, as well as the pigments used.

The most sensitive layer with respect to changes in environment during excavation is the double-layered ground. Loss of water first causes a drastic shrinkage in volume and peeling off from the terra-cotta ("crocodile craquelé"), then the creation of strongly buckled flakes that separate from the terra-cotta substrate (Figs. 5, 6). After drying out, the ground is extremely brittle and breaks very easily. Between the ground and the pigment layers is a recognizable loss of adhesion; movement of the ground causes the pigment layer on top to crack off. After drying, the pigment layer powders when touched lightly.

Conservation Proposal

In the development of a conservation proposal, recognition that the ground was extremely sensitive to humidity was the most important starting point. On one hand, the ground layer must be stabilized against shrinkage during drying; on the other hand, the adhesion and cohesion of the

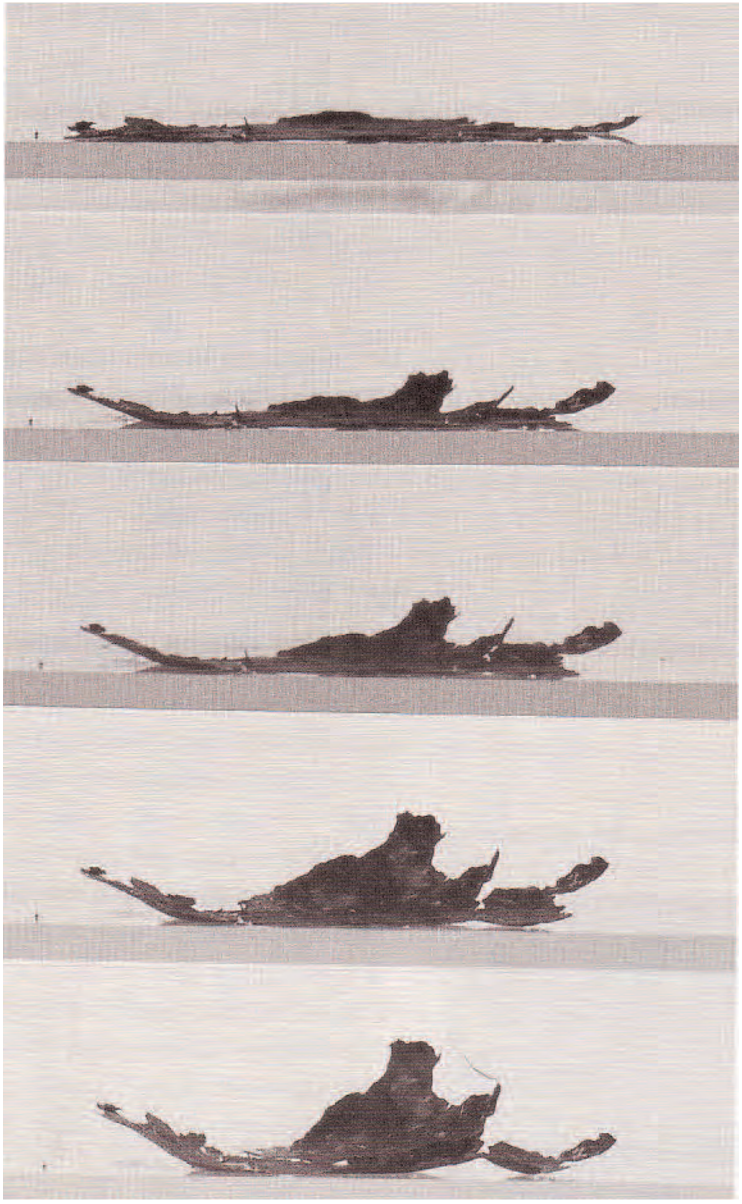

Figure 5
A ground flake (length of the flake when moist: 12 mm) was taken out of the exsiccators with 99% RH and placed in room conditions of about 60% RH. Within four minutes it had buckled considerably, as shown.

Figure 6
Fragment 002-1991 at ca. 60% RH, maximum length 13.5 cm (pit 3 – N0264), showing typical damage to the paint layers.

entire polychromy must be improved or reestablished. Additionally, a technique must be developed to remove the covering of soil from the painted layers in such a way that their original, aged surface is completely preserved. As the basis for the present conservation proposal, the authors formulated the following requirements:

- understanding how the polychromy reacts to slow drying—this will also determine the appropriate point in time for consolidation of the paint layers;
- development of a drying technique;
- stabilization of the ground against shrinkage due to water loss;
- repairing any loss of adhesion between ground and pigment layers;
- repairing any loss of adhesion between ground and terra-cotta substrate;

- repairing any loss of cohesion within the pigmented layers; and
- removal of the soil covering the surface of the paint layers.

Removal of soil from the painted surfaces

Various soil materials adhere to the surfaces of the fragments. Fine-grained, mudlike earth can be removed easily by fine brushes but leaves a residue on the paint surface that makes it appear "yellowed."

Slow drying and determination of the appropriate time for consolidation

Fragments with single-layered grounds can be dried without having to be consolidated beforehand. During the course of slow drying, fragments with double-layered grounds showed a loosening of the paint layers starting at 95% relative humidity (RH), and the polychromy fell off at around 84% RH. Consolidation of the paint layers must be done while the layers are still wet and carried out in humid, saturated air.

Consolidation and demoisturization

The work was done in an enclosed, climate-controlled workbench (at about 99% RH), and the fixing media were applied warm. The greatest difficulty in the consolidation work was the impermeability of the damp, double-layered ground. A good distribution of fixing medium was only achievable on the edges of the craquelure and on the cracks. The following consolidation materials were tested: carboxymethylcellulose, isinglass (fish-bladder glue), Chinese isinglass, Chinese gelatin, and synthetic resins. The best adhesion was achieved with Chinese isinglass.

Through slow drying, an attempt was made to limit the rate at which extreme movements of the ground took place. Paint layers with single-layered grounds could be dried without any problems. After the consolidation work was finished, the first series of experiments in slow drying rates was started. Various salt solutions were studied in exsiccators at different levels of relative humidity (the levels differed in steps of 10% RH). Although the fragments examined in Munich were very small, it took about four weeks to remove the water, regardless of the humidity level. This means that for larger fragments, drying times could run to several months.

For the purpose of developing a method that could be easily implemented on-site, a process of slow drying in boxes of sand was tried. The painted side of the fragment was covered with plastic wrap. The fragment was then placed, painted side down, into a sandbox and covered with slightly moist sand. Under the pressure of the sand, water evaporates slowly out of the ground layer through the terra-cotta. For fragments with a single-layered ground, these methods can be a practical and simple solution (Fig. 7).

Figure 7
Fragment 002-1992. State of preservation after the conservation work at ca. 60% RH.

Freeze-drying

This experiment used freeze-drying to dry and consolidate double ground layers that were saturated with moisture. Normally, freeze-drying is done in two steps: freezing, then drying. As a test material, two flakes of double-

layered ground were placed on a substrate of paper and frozen in the freezer compartment of a refrigerator for about twenty minutes at −20 °C. Then the samples were put into the drying unit of a freeze-dryer and cooled to a temperature of about −45 °C (final pressure: 0.04 mbar). The drying process lasted about two hours. The freeze-drying produced the best results thus far in preserving the double-layered ground. Several tests of this process need to be done to optimize the drying conditions.

Next Steps and Questions

Scientific examinations

Further research needs to take place to

- develop appropriate analytical procedures for clear identification of the material composition of the ground and of the binding media in the pigmented layers; and
- investigate the effects of organic additives on oriental lacquer and the aging of the binding media mixtures.

Conservation work

To appropriately conserve excavated terra-cotta figures, further work needs to be done, including

- investigation of other fragments for a more complete understanding of the composition of the paint surface;
- experiments with freeze-drying with the aim of optimizing drying conditions; and
- adaptation of laboratory results to the excavation situation in Lintong for use in on-site restoration workshops and in a proposal for developing a suitable infrastructure for on-site restoration work.

Conclusion

According to today's state of knowledge, a further excavation of the terra-cotta army would have harmful effects on the colored layers, as the risks connected with the climatic problems during excavation have still not been overcome. Conservation of the polychromy can only be ensured if the excavations are carried out according to the capacity of the equipment and in accordance with all other knowledge of conservation developed during this and any further research.

Acknowledgments

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Judy Greenfield received her diploma in archaeological conservation from the University of Durham, England, in 1989. She was objects conservator at the Rocky Mountain Conservation Center prior to establishing a private practice in 1995. She has worked as a conservator at the Ancient Monuments Laboratory, Edinburgh; English Heritage, London; and the Horniman Museum, London. While her background is in archeological conservation, her scope has expanded to include ethnographic and historic materials as well as collections-care concerns.

Gerd Gudehus studied civil engineering in Berlin, where he also completed his doctoral thesis in soil mechanics. In 1973, he became full professor and chairman of the Department of Soil Mechanics and Foundation Engineering at the Institute of Soil and Rock Mechanics, Karlsruhe University. He is head of the Soil Mechanics Section of the German National Geotechnical Society and is engaged in the conservation and restoration of historical retaining walls and in the stabilization of the foundations of historical buildings situated on soft ground. He is also working on a research project of the German Ministry for Science and Technologies in which the Dafosi grotto is included.

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Jiang Huaying is deputy general engineer and deputy director of the Grotto Conservation Department of the People's Republic of China and is a senior engineer with the Chinese National Institute of Cultural Property. He has headed or participated in numerous projects involving the conservation and maintenance of grottoes, ancient towers, and ancient buildings, such as the Longmen grottoes, Luoyang; the Yungang grottoes, Datong; the Shumi Mountain grottoes, Ningxia; the Kizil grottoes, Xinjiang; the Three Pagodas, Dali, Yunnan; the Ningchen, Inner Mongolia; the Potala Palace, Tibet; and the Taer Temple, Qinghai.

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Sadatoshi Miura is a conservation scientist and director of the Department of Conservation Science, Tokyo National Research Institute of Cultural Properties. He is a member of the Technical Committee for the Joint Conservation Project of Mogao Grottoes between China and Japan. His main research interests include microclimate and nondestructive examination.

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Ingrid Neuman, associate conservator of objects at the Williamstown Art Conservation Center, received her B.A. from the University of Massachusetts in Amherst and her M.A., C.A.S. from the State University College at Buffalo. She has been employed by both the National Museum of Natural History and the National Museum of American History in Washington, D.C., prior to assuming her current position. She has conducted numerous workshops on exhibition and storage techniques for three-dimensional objects and has taught in the Williams College Graduate Programs "Introduction to Art Conservation" course.

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Stephen Rickerby received his M.A. in art history before undertaking the Courtauld Institute of Art–Getty Conservation Institute postgraduate diploma in the conservation of wall paintings, followed by a one-year Courtauld Institute–GCI internship working as a conservator for English Heritage and member of the GCI Tomb of Nefertari project in Egypt. He remained with the Nefertari project until its completion in 1992 and has worked as a private wall-paintings conservator in various countries since 1989.

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Chie Sano is a senior researcher at the Tokyo National Research Institute of Cultural Properties. He graduated from the Chemistry Department of the University of Tokyo. His background is in chemistry and his chief interest is the analytical chemistry of cultural objects.

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Sharon Sullivan initiated and managed the Cultural Resource Management Unit of the New South Wales National Parks and Wildlife Service, which is responsible for the management of Aboriginal and historic places in New South Wales. Later, she became a regional manager for the service, and then deputy director. She is now director of the Australian Heritage Commission, responsible for the development of a comprehensive register of areas of cultural and natural significance in Australia and for the promotion of its conservation. She has worked in the area of cultural resource planning throughout Australia and has published and lectured extensively in this field.

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Wang Jinyu, assistant research fellow with the Dunhuang Academy, has been working in the conservation of the Dunhuang grotto relics for seventeen years. He has been engaged in a number of provincial and international (China–Japan and China–U.S.) collaboration projects. He received a bronze medal from the State Bureau of Cultural Relics and a medal from the Chemical Engineering Ministry. He has written more than fifty scientific reports and publications.

Wang Wanfu is a junior botanist. After graduating from the Lanzhou University in 1992, he joined the Dunhuang Academy. Since then, he has been in charge of monitoring and maintenance programs for both synthetic and vegetation windbreak fences.

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Biographical information was unavailable for Cheng Huaiwen, Duan Xu Xe, Huang Jizhong, and Li Tie Chao.

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